Ecosystems and Environment Research Programme
Faculty of Biological and Environmental Sciences
Doctoral Programme in Sustainable Use of Renewable Natural Resources (AGFOREE)
University of Helsinki

Telecouplings in a globalizing world: linking food consumption to outsourced resource use and displaced environmental impacts

Vilma Sandström

ACADEMIC DISSERTATION

To be presented for public examination with the permission of the Faculty of Biological and Environmental Sciences of the University of Helsinki in Auditorium XII, University Main Building on 21 November at 12 noon.

Helsinki 2018

Supervisor

Professor Pekka Kauppi, University of Helsinki

Advisory Committee

University Lecturer Risto Willamo, University of Helsinki
Docent Laura Saikku, Finnish Environment Institute

Pre-examiners

Professor Olli Varis, Aalto University
Professor Peter H. Verburg, VRIJE Universiteit Amsterdam

Opponent

Associate Professor Martin Persson, Chalmers University of Technology

Custos

Associate Professor Sirkku Juhola, University of Helsinki

Grading committee

Associate Professor Martin Persson, Chalmers University of Technology
Associate Professor Sirkku Juhola, University of Helsinki
University Lecturer Sirkku Manninen, University of Helsinki

Cover photo: Vilma Sandström

ISSN 2342-5423 (Print)
ISSN 2342-5431 (Online).
ISBN 978-951-51-4662-5 (paperback)
ISBN 978-951-51-4663-2 (PDF)

Electronic publication at http://ethesis.helsinki.fi

Unigrafia Oy, Helsinki 2018

Abstract

Globalization has increased the interconnections between world regions. The distal socio-economic and environmental interactions, feedbacks and outcomes between land systems are called *telecouplings*. The increase in telecouplings is also true with agricultural production and food systems as food trade has intensified in the past decades. This change has contributed to many positive aspects of development for example by increasing food availability and creating employment in the production areas. However, it has also increased the spatial separation between consumption and production and consequently the displacement of environmental pressures as consumers from distant locations withdraw limited resources such as land or water from the production areas. Therefore, consumption can be a driver of environmental change also in geographically distant locations.

In this dissertation the focus is on the quantitative analysis of the displaced environmental pressures through international trade related to Finnish food consumption, and the development of accounting methodologies to better account for the implications of trade. The dissertation consists of four research papers and a synthesis of them. The temporal dynamics in 1961-2007 (Paper I) and 1986-2011 (Paper II) of the displaced impacts of the Finnish food consumption are analyzed with a data from physical accounting applying land and water footprints and studying the related biodiversity impacts caused in the production areas. Paper III concentrates on analyzing the potential to replace some of the imported crops with domestic production and this way decreasing the imports of virtual water from water scarce production areas. Paper IV contributes to the methodological discussion presenting an analysis of the carbon footprints of the average diets in the EU countries using a novel framework that incorporates trade flows into carbon footprint accounting.

Finland has become strongly connected to global agricultural market. Both the imports and exports of land use embedded in the Finnish agricultural trade expanded and the partner countries and products imported diversified during 1961-2011. This was particularly clear in the period of 1986-2011 when the land use embedded in the Finnish crop imports nearly doubled. Highest increase in imports was observed with crops that can be, and previously have been cultivated in Finland. The majority of the threats to global biodiversity caused by the Finnish food consumption were produced outside the Finnish borders highlighting therefore the need to account for these distant impacts. Trade relations are not always based on resource efficiency, and water abundant Finland also imports water intensive products from areas suffering from water scarcity. There is potential for substantial reductions in the Finnish virtual water imports replacing some of the imports with crops from domestic production. Animal products, especially beef and dairy consumption are related to the highest share of dietary carbon footprints of the average diets in the EU countries. Their production requires also higher land and water inputs compared to average plant based products. Therefore, a reduction of animal product consumption is an efficient way of reducing the environmental impacts of food consumption.

The findings of this dissertation confirm and extend previous knowledge quantifying the globalization of the Finnish food system that is increasingly depending on the sustainability of also the food systems abroad. Therefore, comprehensive analyses integrating multiple indicators and different spatial scales are increasingly needed to support sustainable food systems locally as well as globally.

Tiivistelmä

Globalisaation myötä maantieteellisten alueiden väliset yhteydet ovat lisääntyneet. Kaukaisia ympäristö- ja yhteiskunnallis-taloudellisia vaikutuksia, takaisinkytkentöjä sekä seurauksia maantieteellisten systeemien välillä kutsutaan termillä *telecouplings*. Tällaisten yhteyksien kasvu näkyy myös maataloustuotannossa ja ruokasysteemeissä, sillä ruoan maailmankauppa on kasvanut voimakkaasti viime vuosikymmenten aikana. Tämä muutos on vaikuttanut positiivisesti kehitykseen mm. lisäämällä ruoan saatavuutta sekä luomalla työllisyyttä tuotantoalueilla. Muutos on kuitenkin myös lisännyt kulutuksen ja tuotannon maantieteellistä eriytymistä ja tämän seurauksena ympäristön käytön paineen ulkoistamista, kun myös maantieteellisesti kaukana olevat kuluttajat käyttävät tuotantoalueen rajallisia resursseja, kuten vettä tai maa pinta-alaa. Tämän takia kulutus voi aiheuttaa ympäristövaikutuksia myös maantieteellisesti kaukana sijaitsevilla alueilla.

Tässä väitöskirjassa keskiössä on analyysi suomalaisten ruoankulutuksen aiheuttamasta ulkoistetusta ympäristön käytön paineesta sekä ruoankulutuksen hiilijalanjälkilaskennan kehittäminen niin, että kaupan materiaalivirrat otetaan siinä paremmin huomioon. Väitöskirja koostuu yhteenveto-osasta sekä neljästä osa-julkaisusta. Työssä analysoidaan Suomen ulkomaankaupan kautta ulkoistettujen ympäristövaikutusten ajallista muutosta vuosina 1961–2007 (osajulkaisu I) sekä 1986–2011 (osajulkaisu II) käyttäen kansainvälisen kaupan fyysisten materiaalivirtojen analyysidataa sekä maa- ja vesijalanjälki-indikaattoreita, ja analysoimalla näiden resurssien käytön aiheuttamaa biodiversiteettikadon uhkaa tuotantoalueilla. Osajulkaisussa III tutkitaan Suomen potentiaalia vähentää kasvituotteiden tuonnin kautta virtuaalivettä vesipulasta kärsiviltä alueilta korvaamalla tuotteita kotimaisella tuotannolla. Osajulkaisussa IV kehitetään ruoan kulutuksen hiilijalanjälkilaskentaa ja analysoidaan EU maiden keskimääräisten ruokavalioiden hiilijalanjälkiä sisällyttäen kaupan materiaalivirta-analyysit mukaan laskentaan.

Suomi osallistuu yhä vahvemmin globaaliin maataloustuotteiden kauppaan. Sekä maankäytön tuonti että vienti Suomen maataloustuotteiden ulkomaankaupassa laajeni ja tuojamaat sekä tuodut elintarviketuotteet monipuolistuivat vuosien 1961–2011 aikana. Tämä oli erityisen voimakasta ajalla 1986–2011, jolloin tuonnin kautta ulkoistettu maankäyttö lähes kaksinkertaistui. Suurin kasvu oli nähtävissä tuotteilla, joita voidaan kasvattaa ja joita on aiemmin tuotettu Suomessa. Suuri osa suomalaisten ruoan kulutuksen aiheuttamista uhista lajien monimuotoisuudelle aiheutuu Suomen rajojen ulkopuolella, mikä korostaa näiden ulkoistettujen vaikutusten huomioimisen tärkeyttä. Kauppasuhteet eivät aina perustu resurssitehokkuuteen ja mm. vesivaroiltaan runsaaseen Suomeen tuodaan paljon vettä vaativia tuotteita kuivuudelta kärsiviltä alueilta. Suomella on potentiaalia toteuttaa huomattavia vähennyksiä veden tuonnissa korvaamalla osa tuonnista kotimaisella tuotannolla. Eläinperäiset tuotteet, erityisesti naudan liha ja maitotuotteet, aiheuttavat suurimman osan keskimääräisen ruokavalion hiilijalanjäljestä. Niiden tuotanto vaatii myös suuremman määrän maata ja vettä verrattuna kasviperäisiin elintarvikkeisiin. Tämän takia eläinperäisten tuotteiden kulutuksen vähentäminen on tehokas keino vähentää ruoan ympäristövaikutuksia.

Tämän väitöskirjan tulokset vahvistavat ja laajentavat aikaisempaa ymmärrystä Suomen ruokajärjestelmän globalisaatiosta, jonka kestävyys on yhä voimakkaammin riippuvainen myös ulkomaisten ruokajärjestelmien kestävyydestä. Tämä takia tarve kokonaisvaltaisille, useampia indikaattoreita sekä erilaisia maantieteellisiä mittakaavoja yhdistäville analyyseille on kasvanut ja niitä tarvitaan tukemaan sekä paikallisesti että globaalisti kestäviä ruokajärjestelmiä.

Acknowledgements

The idea of starting my PhD studies emerged from the concern of the global environmental crisis and the desire to find ways to change our societies into a more sustainable direction. I was curious about the hidden impacts related to our everyday activities, such as eating, and wanted to understand the world better. This journey has taught me to understand, criticize and value research and science. I have also learned to challenge my own thinking and understand the importance of including various perspectives and scales into every question because everything is connected. Now finalizing my PhD studies, I understand how this path is a life-long learning process and I am grateful for all the lessons already learned from and with the many inspiring people that I have had the honor to meet and work during this journey. This thesis would not have been possible without the collaboration, co-creation and sharing of knowledge, ideas, advices, perspectives and discussions with all the great people I have met. Therefore I want to express my deepest gratitude especially to the people mentioned here, but also to all others who have contributed to this work one way or another.

First of all, I would like to thank my supervisor Professor Pekka Kauppi for supporting me and guiding me throughout the process since the beginning. You were always ready to help and shared your knowledge and contact networks with me. Thank you also for trusting me with the organization and teaching of my first Masters' level courses. In short, thank you very much for always believing in me! Also, I want to thank university lecturer Risto Willamo, Ripa. I admire your wisdom and spirit and your way of guiding me and other students to dig deeper and finding the individual strengths and potentials in each one of us. You taught me how important it is to change perspective and scale to understand connections and interrelations always keeping in mind the bigger picture. You were truly my most inspiring mentor throughout the whole learning process.

As well, I would like to express my gratitude to Associate Professor Martin Persson from Chalmers University, Sweden for giving me to honor to have you as my opponent. I would also like to thank Professor Olli Varis from Aalto University and Professor Peter H. Verburg from Vrije University Amsterdam, the Netherlands for taking the time to read my thesis and for the very encouraging comments and good suggestions for improvements. I addition, I want to thank Sirkku Juhola, for accepting to be my Custos and guiding me with all the practical issues related to the defense. Also thank you university lecturer Sirkku Manninen for being part of the grading committee of this dissertation.

Docent Laura Saikku from the Finnish Environment (SYKE), thank you for co-authoring a paper with me, for accepting to form part of my advisory committee and for guiding me in my doctoral studies. I want to thank also Riina Antikainen (SYKE) and Laura Sokka (VTT) for co-authoring the first paper of this dissertation with me and this way opening the door to the research world for me.

My doctoral studies were funded for three years by the Doctoral Programme of Sustainable Use of Renewable Natural Resources (AGFOREE) of the University of Helsinki that belongs to the Doctoral School in Environmental, Food and Biological Sciences (YEB). I want to thank AGFOREE and YEB for all the support, for organizing very useful courses and events, and for providing travel grants to attend international conferences.

During this journey I have had the honor to work with highly talented researchers. I want to express my deepest gratitude to Thomas Kastner from Senkenberg Institute of Biodiversity and Climate, Frankfurt. You co-authored two of the research articles of this thesis and your research also worked as a base for a third one. Your expertise, talent and kindness shaped my thinking about how scientists should be. Thank you! Thank you also Assistant Professor Laura Scherer from Leiden University for co-authoring a paper and sharing your ideas with me. Also, during my doctoral studies I had the privilege to participate in the Young Scientists Summer Programme 2016 at the International Institute of Applied Systems Analysis IIASA in Austria, working there under the supervision of Hugo Valin. Thank you Hugo for guiding me and giving me the opportunity to learn from your extended expertise. Also I want to thank my co-supervisor Tamás Krisztin for all your help, and Petr Havlik and Mario Herrero (CSIRO) for sharing your data and co-authoring the last paper of this dissertation with me.

Similarly I want to thank Pirjo Peltonen-Sainio from the Natural Resources Institute of Finland, for being always so optimistic, encouraging and inspiring collaborator and co-author. Also, doctoral student Elina Lehikoinen from Aalto University, thank you for sharing with me the ups and downs with our study. Your positive energy and the effort you put in our work was truly an inspiration for me! Also I want to thank Matti Kummu from Aalto University for your guidance, for the always on-point advice and your kindness. Also, I want to thank Kaisa Korhonen-Kurki for being always so positive and contracting me to the KOKIJA project this way providing me with the opportunity to learn about the world of science communication while finishing my dissertation.

A big thanks goes to all my friends and colleagues. Thank you researchers and doctoral students from EcoEnv, FEM, UEP and UERG research groups for your help and all the inspiring lunch discussions. Anna Salomaa, thank you for sharing the office and our everyday thoughts for the last year. In addition to my own research, I have been fortunate to work with Kudelma-network for comprehensive and sustainable change and study the power of comprehensive thinking to change the world. Thank you especially Liisa Haapanen, Leena Helenius, Annika Nuotiomäki, and all others not mentioned here, for sharing your ideas and giving me the opportunity to learn so much from you.

This journey in the world of science would have been a lot heavier without the balancing company of my best friends Saara, Pinja, Salla and Julia. Thank you for dragging me out of the academic bubble, for giving me always the best laughs and for just being you. I love you girls! Also big thanks for my sisters and brother Vappu, Varpu, and Otto and Laura and Veera and my mom Leea and dad Matti for always supporting me and encouraging me. Also, a huge thanks goes to our family in Ecuador: Daysi thank you for all your help while we were living in Ecuador in 2017, and Roci and Ramiro thank you for coming all to way to Austria to take care of our daughters for three months and this way allowing me to work at IIASA! I am in forever debt with you.

Furthermore, I want to thank my closest circle, my two biggest teachers in life, our daughters Amelie and Ilona (you are now about as old as this PhD project!). Your way of seeing the world always reminds me how lucky we are and how we can find miracles everywhere. And last but not least, my husband Paul, thank you for loving me, for always being there for me and for sharing this path of life with me.

Finally thank you all the wonderful people who work with transforming the world to a more sustainable direction! Keep up inspiring people and striving for change!

Helsinki, November 2018
Vilma Sandström

Contents

List of original publications

This thesis consist of the following four publications and a synthesis of them. The articles and manuscripts will be referred to in the text as Papers followed by their roman numerals:

Paper I: Sandström, V., Saikku, L., Antikainen, R., Sokka, L., & Kauppi, P. (2014). Changing impact of import and export on agricultural land use: the case of Finland 1961–2007. *Agriculture, Ecosystems & Environment,* 188, 163-168. doi.org/10.1016/j.agee.2014.02.009

Paper II: Sandström, V., Kauppi, P. E., Scherer, L., & Kastner, T. (2017). Linking country level food supply to global land and water use and biodiversity impacts: The case of Finland. *Science of the Total Environment,* 575, 33-40. doi.org/10.1016/j.scitotenv.2016.10.002

Paper III: Sandström, V., Lehikoinen, E., & Peltonen-Sainio, P. (2018). Replacing imports of crop based commodities by domestic production in Finland: Potential to reduce virtual water imports. *Frontiers in Sustainable Food Systems,* 2:67. doi.org/10.3389/fsufs.2018.00067

Paper IV: Sandström, V., Valin, H., Krisztin, T., Havlik, P., Herrero, M., Kastner, T. (2018). The role of trade in the greenhouse gas footprints of EU diets. *Global Food Security,* 19, 48-55. doi.org/10.1016/j.gfs.2018.08.007

Authors’ contributions

	I	II	III	IV
Original idea	VS, PK	VS	VS, EL, PP	VS, HV, TKr
Study design	VS, PK	VS	VS, EL, PP	VS, HV, TKr
Data	VS	VS, LSc, TK	VS	VS, HV, TKr, TKa, MH, PH
Methods and implemention	VS	VS, LSc, TK	VS	VS, HV, TKr
Manuscript preparation	VS, LSa, LSo, RA, PK	VS, LSc, TK, PK	VS, EL, PP	VS, HV, TKr, TKa, MH, PH

EL: Elina Lehikoinen
HV: Hugo Valin
LSa: Laura Saikku
LSc: Laura Scherer
LSo: Laura Sokka
MH: Mario Herrero
PK: Pekka Kauppi
PH: Petr Havlik
PP: Pirjo Peltonen-Sainio
RA: Riina Antikainen
TKr: Tamas Krisztin
TKa: Thomas Kastner
VS: Vilma Sandström

Paper I: V.S. planned and designed the study together with her supervisor Pekka Kauppi. V.S. gathered the data and implemented the analysis. She also prepared the manuscript together with the help and guidance of the co-authors.

Paper II: V.S. designed and planned the study. She used data from studies of T.K. and L. Sc. and together with them applied the data analysis. She visualized the data and prepared the manuscript with the help of the co-authors.

Paper III: The study was designed by all three authors. V.S gathered the data and conducted the data analysis. V.S and E. L visualized the data. All three authors contributed to the interpretation of the results and the writing of the manuscript.

Paper IV: V.S, H.V and T.Kr designed the research. All authors prepared the data required for the calculation. V.S implemented the method and performed the calculations. V.S., H.V. and T.Kr. analyzed the results. V.S. wrote the article with the in-depth editing and key recommendations from the other authors.

1. Introduction

And before you finish eating breakfast in the morning, you've depended on more than half of the world. (Martin Luther King Jr)

1.1. Complex sustainability problems and the increased globalization

Human activities drive environmental change on the Earth's ecosystems and climate in an unwitnessed scale (Crutzen et al., 2002; Rockström et al., 2009; Steffen et al., 2007; Steffen et al., 2015). As a consequence, societies all over the world are facing complex intertwined challenges such as climate change, natural resource depletion, biodiversity loss and rapid urbanization. These kind of challenges have spatially and temporally wide drivers and impacts and complex interconnections between them. They can have multiple possible formulations, often no easy solutions and unpredicted outcomes and feedbacks sometimes at different systemic levels or geographic scales.

In the post green revolution era, the global population has more than doubled from 3 billion people in 1960 to 7.5 billion in 2017 (FAO, 2018). At the same time population living in urban areas have increased from 33% in 1960 to 54% in 2016 (World Bank, 2018). Simultaneously with the overall increase in population, the spatial separation between human population and the sources of natural resources consumed has increased (see e.g. Kissinger and Rees, 2010; Reid et al., 2005). This creates another level of complexity when assessing the sustainability problems, as it is often difficult to draw the line between the drivers of change (e.g. consumption choices in one country) and their consequences (e.g. deforestation in another country and the consequent biodiversity loss and climate change impacts) (see e.g. Meyfroidt et al., 2013).

This increased spatial separation of consumption from production has been enabled by the intensification of global trade that connects world regions through material flows transported by international trade (Liu et al., 2013; Kastner et al., 2014a). Many exported goods are not consumed in the country that imports them but exported further to third countries. Hence, the average number of country borders crossed by the exported goods is showing an increasing trend (Zhang et al., 2017). Almost a third of global material use (Wiedmann et al, 2015), a quarter of the global land use (Weinzettel et al., 2013), 20-30% of global water use (Lenzen et al., 2013) and 20-25% of the global greenhouse gas (GHG) emissions (Wood et al., 2018; Peters & Hertwich, 2008; Hertwich & Peters, 2009) are embedded in traded products.

Globalization has many dimensions, for example cultural globalization (e.g. the unification of lifestyles) or ecological globalization (e.g. spreading and expansion of certain species to new areas). But here, by globalization I refer mostly to the development of increasingly integrated global economy and culture where spatial connectivity and the links across national boundaries between processes and consequences have increased (Al-Rodhan and Stoudmann, 2006: Kissinger and Rees, 2010). The change has been enabled by trade liberalization, progress in transport and information technology and reductions in governmental regulation of trade (Anderson, 2010).

The increased globalization can impact and have consequences on people and ecosystems in many different ways that can be seen both positive and negative depending on the point of view. For example, trade has increased food availability for many countries and regions (Porkka et al., 2013). Also, the production regions can benefit from the increased globalization when the production of exported goods create employment and contribute to the economic growth and development of the area. Economists often see globalization as a way of increasing wealth creation (e.g. Das, 2004). It has been suggested that global integration of trade, finance and investment can improve livelihoods and wellbeing and therefore contribute to the environment providing the necessary pay for environmental improvements (Bhagwati, 2004; Das, 2004). However, while economic development can lead to greater investment in local environmental quality, at the same time the increased affluence intensifies natural resource use and ecological risks both locally and in distant regions with the increasing outsourcing of land use abroad (Meyfroidt et al., 2010; Weinzettel et al., 2013, see also Haapanen & Tapio, 2016 for an analysis of the contemporary economic growth critique). These impacts are only visible when the displacement of land use though trade is taken into account (see e.g. Mayer et al., 2005; Mayer et al, 2006).

The displacement of resource use and the related environmental impacts are often easily neglected. This is partly because of international trade that adds another level of complexity to food systems, transporting raw materials and commodities in global trade. Understanding this kind of complexity is difficult because of, at least, two reasons. First, from a consumer point of view, the evolution has shaped the human brains to respond to present and nearby impulses (Heerwagen & Orians, 1993). The spatial separation of production from consumption eliminates some of the signals or the negative feedbacks created in the supporting ecosystems from reaching the consumers (Kissinger and Rees, 2010). Therefore, increasing spatial or temporal distance to threats and impacts makes their understanding difficult (Goleman, 2009, 32-34). Second, western science has for centuries been dominated by specialized approaches focusing on the analysis of details instead of understanding complex systems and larger wholes (see e.g. Cairns, 2004; Willamo, 2005). Thus, research that increases and expands the understanding of complex systems and the distant impacts of consumption, is needed in order to analyze the underlying drivers of environmental change

1.2. Implications of globalization on food systems

Global food systems face urgent need for changes to provide healthy and nutritionally balanced food for the growing population with lower environmental cost. Globally, the food consumption and the resources used are not divided equally among people. At the same time while more than 800 million people suffer from hunger (FAO, 2017), more than 1.9 billion people are overweight (WHO, 2018). Food systems are also one of the most important sectors causing environmental change. Food system here, is defined as the processes, infrastructure and the inputs and outputs involved in feeding a population including primary production, processing, packaging, transporting, consumption and disposal of food. It also contains the interactions between the biogeophysical and human environments related to all these processes and activities (Ericksen, 2008).

Currently, agriculture is the largest land and water user globally occupying 34% of Earth's terrestrial surface (Ramankutty et al., 2008) and using 70% of global freshwater withdrawals (Döll, 2009). This has had major consequences for natural ecosystems through habitat loss, fragmentation and impacts of agricultural management (Ramankutty et al., 2018). From 1980 to 2000, more than half of new agricultural land in the tropics came from expansion into intact forests (Gibbs et al., 2010). Also, food systems are responsible for approximately 19–29% of total anthropogenic GHG emissions globally (Vermeulen et al., 2012). Additionally, the use of nutrient fertilizers, pesticides and other chemicals in agriculture are major source of freshwater and coastal ecosystems pollution and eutrophication (Ramankutty et al., 2018).

These increasing pressures on the environment have aggravated the severe sustainability problems such as natural resource depletion, climate change and global biodiversity loss (e.g. Rockström et al., 2009; Steffen et al., 2007; Steffen et al., 2015). Behind these problems there are complex combination of drivers. Local degradation can be result of local processes, but also of distant actions taking place in geographically distant places. Consumption in one place can be driving environmental change and even processes such as deforestation, habitat destruction and biodiversity loss elsewhere. For example, export-oriented agricultural production is one of the most important causes of tropical deforestation (DeFries et al., 2010; DeFries et al., 2013). The EU countries imported almost 36% of all global deforestation embodied in crop and livestock products traded between regions over the period 1990-2008 (Cuypers et al., 2013). Up to a third of global species threats are due to the displacement effect of international trade (Lenzen et al., 2012). Therefore most of the major environmental problems such as biodiversity loss should be examined as global phenomena instead of analyzing them in isolation within the country borders. In a globalized world, the sustainability of a region increasingly depends on the ecological sustainability of other regions both directly and indirectly (Kissinger and Rees, 2010).

The increased globalization is especially clear with agricultural products and food industry. Calories traded in the material flows of food imports and exports more than doubled from 1990 to 2015 and currently about a fourth of all food produced is traded internationally (D'Odorico et al., 2014). Approximately 80% of the global population lives in countries that import more agricultural products than they export (Porkka et al., 2013). During 1986-2009 land use occupied by production for exports grew rapidly (by about 100 Mha) while land used for domestic consumption remained virtually unchanged (Kastner et al., 2014a).

When a country uses resources from another country or region, they displace their resource need abroad. When accounting for only the production-based impacts, or the impacts caused inside the country borders, these displaced environmental and social impacts are allocated to the production country, although they might be related to consumption of another country. Many national inventories consider only the production-based impacts created inside the country border and do not take into account the imports. A good example of this is the United Nations Framework Convention for Climate Change (UNFCC, 2016), that reports GHGs produced only inside the country borders. This distorts accounting especially within the food sector as an increasing share of global food production is traded internationally (Kastner et al., 2014a; Porkka et al., 2013) and impacts associated with their production are allocated to the exporting country. Consumption based accounting measure the amount of resource use associated with final consumption (Kastner et al., 2014b).

When assessing the consumption based impacts it is important to trace back the food origin, because production areas have differing production practices and land use histories. However, this is often excluded from the environmental footprint or other impact analyses. For example, various studies assessing the GHG emissions of diets use emission factors for average products consumed in a country (see e.g. Perignon et al., 2016), exclude trade and use data from life cycle analysis (LCA) studies based on the production structures of the consumption country (see e.g. Eshel and Martin, 2006; Pradhan et al., 2013) or other advanced industrialized countries (see e.g. Heller and Koelian, 2015; Tom et al., 2016). Such approaches, however, create a bias in the accounting, especially concerning countries that rely heavily on imports for their food supply. For example, Koskela et al.

(2011) concluded that the impacts of imports are underestimated when using domestic emission intensities for their accounting due to the high level of environmental protection in Finland.

1.3. The focus and aims for this thesis

This dissertation contributes to enhancing the understanding about the implications of international trade to sustainable food consumption by presenting quantitative analysis of the environmental pressures displaced through international trade. The focus is on the analysis of the Finnish food imports (Papers I-III) and on the GHG footprints of the EU diets (IV).

Finland is situated in North of Europe in the high latitudes (approximately between 60°N and 70°N). The climatic conditions in Finland are characterized with long, dark winters and short growing season in summer with abundant daylight. Finland is relatively self-sufficient with some food commodities and also produces crops for exports, particularly cereals (FAO, 2018). However, due to climatic restrictions to domestic agriculture, many crops, such as coffee, soybeans, corn, many fruits etc. cannot be produced domestically and have to be imported from abroad. From the point of view of the social dimensions of sustainability, Finland is very successful when analyzed with several indicators of well-being, such as long life expectancy and a high level of education (Lyytimäki et al., 2018). However, when focusing on the ecological aspects, the consumption in Finland has exceeded many limits for ecological sustainability (Hoff et al., 2014) as is the case with most of the EU countries (Hoff et al., 2014; O'Neill et al., 2018). Finland outsources a large portion of its material use to other countries (Furman et al., 2018). Therefore, the challenges related to the Finnish food systems need to be analyzed in global context.

This thesis consist of a synthesis and the four independent research articles and manuscripts. The objectives of the dissertation are:

1. To enhance understanding about the role of international trade in food consumption in Finland and its implications to sustainable food consumption
2. To analyze temporal dynamics of land and water use embedded in food imports into Finland and the consequent impacts to ecosystems in the production areas
3. To develop greenhouse gas footprint accounting approach taking into account the material flows in international trade

The objectives are addressed through four original research Papers, which are complemented with this synthesis. The first objective is a more general one, the second one focuses more specifically on the Papers I-III and the third one is more a methodologically oriented aim based on the Paper IV. The research questions addressed in each Paper are detailed in Table 1.

Paper I focuses on analyzing the land use embedded in the Finnish agricultural imports and exports from 1961 to 2007. The historical trends are identified taken into account the trade of both crops and animal products.

Paper II incorporates data from a physical material flow analysis of international food trade to study the embedded land and water use in the crop imports related to Finnish food supply. Additionally also the biodiversity impacts caused by the resource use in the production countries are studied. The trends in imports are analyzed from 1986 to 2011.

Paper III focuses on the virtual water embedded in the Finnish crop imports. A solution oriented approach is adopted to analyze how much of the imported virtual water could be reduced replacing the imports of the three water intensive crops (rice, soybeans and rapeseed) with domestic production of the same or alternative crop.

Paper IV investigates the role of international trade in the GHG footprint accounting. The scope of the study is in the EU countries. The aim is to analyze consumption based GHG footprints of an average food supply in a country through an accounting framework that incorporates data from a trade flow analysis. This way it is possible to account for the GHG footprints using country- and product-specific emission factors.

Table 1. Specific research questions in each Paper and their relation to the overall aims of this thesis

Paper	Questions	Overarching objective
I	How has the land area embedded in the Finnish agricultural imports and exports changed from 1961 to 2007?	1, 2
II	How have the crop imports into Finland changed from 1986 to 2011? What are the foreign production regions for these products? How much land and water use has been outsourced and what are the global biodiversity impacts caused by these resource uses?	1, 2
III	How has the Finnish displaced water use pressure changed from 1986 to 2011? What are the most important crops with the highest embedded virtual water imports into Finland? How much of the virtual water embedded in imports could be reduced by harnessing the potential in Finland to replace imports of rice, soybeans and rapeseed with domestic production of the same or alternative crops? How much would this replacement reduce the water use pressure in the production regions, especially focusing on the water scarce regions?	1, 2
IV	How GHG intensive are the average diets in the EU countries? How does international trade impact the dietary emissions accounting?	1, 3

2. Philosophical, theoretical and methodological framework

2.1. Philosophical assumptions

It is useful for every researcher to clarify and explain for the readers the paradigm and philosophical approach behind their research. By paradigm, I refer to the set of principles, values and beliefs that form the base for theories and methodologies chosen by the researcher (Guba, 1990). By philosophical approach, I refer to the whole formed by the paradigm and its application, similarly as in Willamo (2005, 15). They affect the choice and framing of research subjects and also to the way the researcher describes and analyzes them. Additionally they affect researcher's understanding of what kind of information can be obtained through inquiry and what kind of conclusions and recommendations can be drawn. This is especially true in research fields such as environmental and sustainability sciences that have strong policy connections. Therefore, it is useful to also separate the *ontological*, *epistemological* and *axiological* standpoints (see e.g. Archer et al., 2013, xiii).

The main philosophical assumptions that this thesis is based on, follow the tradition of critical realism, as categorized e.g. by Guba (1990). The term realism refers to ontology and, most of all, refers to a view that reality outside human mind and language does exist and is driven e.g. by natural laws (see e.g. Guba, 1990). For example, the carbon dioxide molecules and the increase in their atmospheric concentration or the transportation of agricultural products between countries are ontologically real and not only constructs in human mind.

The criticalness as a dimension of the approach, refers to the idea of acknowledging the limitations of our epistemological means. It is impossible for humans truly perceive the reality with our imperfect sensory and intellective mechanisms, and the findings, e.g. in science, emerge from the interaction of the inquirer and the inquired (see e.g. Guba, 1990). However, the approximation of reality is possible and it should be approached as neutral as possible, presenting the researchers predispositions for the reader. This is reflected in this thesis, for example, in the following manner. The complexity of the large socio-ecological systems (see e.g. Young et al., 2006a and 2006b) makes the exact addressing of causalities almost impossible. Nearly all sustainability issues, such as the environmental impacts of food consumption analyzed in this study, have highly complex and often unexpected relations between an action and its consequence. Therefore, we cannot undoubtedly say that food consumption in Finland has contributed to the species extinction or greenhouse gas emissions production in another country. However, this does not mean that the use of this kind of indicators would be useless, quite the contrary. Although acknowledging all the limitations and simplifications of the research methods, the use of the indicators, such as the ones applied in this thesis, can be very useful and eye-opening in addressing the underlying drivers of environmental change.

Finally, it is valuable for a researcher to analyze their grounds from axiological point of view, referring to axiology as the philosophical study of values. This is important e.g. in order to understand the nature of objectivity that can be achieved. Following the tradition of critical realism, it is considered that the objectivity in research remains always an ideal and can only be approximated because inquiry acts are affected by the values of the researcher (see e.g. Guba, 1990). This is especially relevant for sustainability science, where reflexivity is essential, because it is acknowledged that the paradigms endorsed and the type of questions asked are driven by the definition of the field "to be responsive to the needs and values in society while preserving the life support systems of planet Earth" (Kates et al., 2001, see also Spangenberg, 2011). Sustainability science is therefore purpose-bound as opposed to some natural sciences that traditionally have been considered as 'value free' (Spangenberg, 2011).

In addition to addressing the philosophical assumptions behind the research approach, I add systemicness, as a dimension that is affecting the paradigm chosen, above all from the epistemological and ontological perspectives. By systemicness I refer to the systemic thinking tradition where reality can be seen as systems, in which entities are organized as parts and wholes (see e.g. Flood et al., 2010; Ison, 2010). There are both horizontal and vertical interconnections between the parts and wholes that create complexity in the system (Willamo et al., 2018). Willamo et al. (2018) use comprehensive thinking as an upper level term for various kind of onto-epistemological approaches that emphasize integrative, broad approaches. Systemic thinking can be seen as one variant of it. Understanding complexity and the interactions is increasingly needed in science that has been dominated by specialized, narrow approaches for centuries and especially over the past decades (see e.g. Kates et al., 2011; Ostrom, 2009; Willamo et al., 2018). Therefore, more emphasis needs to be set, in addition to the specialized approaches and the analysis of details, to the understanding of the bigger picture. For this, systemic thinking and other variants of comprehensive thinking, e.g. dialectical thinking, are very useful approaches (Willamo et al., 2018). Comprehensive thinking can be added to research at least in three dimensions (see Willamo et al., 2018). First adding various viewpoints and/or objects (e.g. here the impacts of telecouplings on several environmental problems, such as global biodiversity loss, water depletion and climate change), second, focusing on the analysis of the interconnections (e.g. here the consumption-production connections) and third, organizing systems to different hierarchical levels that all have their importance in the analysis (e.g. here local – global).

2.2. Theoretical framework

Sustainability science forms the disciplinary roof for this study. Sustainability science is an over-arching research field incorporating many different sub disciplines from e.g. natural and social sciences (Spangenberg, 2011). It seeks to understand and analyze the fundamental character of interactions between nature and society (Kates et al., 2001). Spangenberg (2011) defines it as "research providing the necessary insights to make the normative concept of sustainability operational, and the means to plan and implement adequate steps towards this end". Therefore, sustainability science is a research field that is characterized by its research purpose more than common research object or methods used (Spangenberg, 2011).

Sustainability science works with complex issues such as climate change, natural resources use, biodiversity loss, urbanization etc. (Kauffman, 2009). These issues are characterized with non-linear effects and delayed responses driving the systems beyond cause-effect logic with feedback and rebound effects that are often difficult to anticipate (Allen, 2001). Therefore, one of the core tasks set for the field is to span the range of spatial and temporal scales between actions and their consequences (Allen, 2001; Kates et al., 2001), which is also the aim of this research.

Nested within the broader scope of sustainability science there is a specific field, land system science that focuses on the land change and the increasingly complex drivers in transforming the earth (Friis et al., 2016). Sustainability science and land system science both deal with the different aspects of sustainability such as environmental, social and economic among others. This study is focused only on the environmental perspective, although it is acknowledged that the economic and particularly social aspects (such as questions related to employment and income) are highly relevant to take into account in future studies for a more comprehensive picture of the implications of food trade. However, it can be argued that the environmental sustainability is the most critical because the other dimensions of sustainability depend on it. The results of this thesis can be seen as part of a broader discussion about sustainability and they should be further strengthened with analyses from economic and social points of view.

Land use at all levels is influenced by long-distance flows of materials, energy and information (Friis et al., 2016). The analytical concepts of teleconnections and telecouplings are in the core of land change science summarizing the spatial connections between processes. The term teleconnection originated over a century ago and has been widely used in meteorology and climate studies indicating the long-distance interactions and connectivity between and across land, ocean, freshwater and atmosphere (Angstrom, 1935; Moser et al., 2015). The use of the term teleconnection was later on broadened to describe also the distal socio-economic and environmental drivers of land use (Seto el al., 2012; Friis et al., 2016). Telecoupling was proposed as a response to more explicitly focus on the feedbacks, multidirectional flows, interactions and outcomes between land systems (Friis et al., 2016; Liu et al., 2013).

A telecoupling between two systems is created when there is a material, energy or information flow from one system to another (Liu et al., 2013). The systems framing is therefore an essential aspect to determine. A system in a broader sense in systems thinking literature can be defined as "a whole whose elements are interconnected" (Ison, 2008, 140). Therefore, system can be understood as a physical entity or a process (Ison, 2008). In a systems thinking view, world is seen as systemic, meaning that 'phenomena are understood to be emergent property of an interrelated whole' (Flood, 2010). Emergence refers to a property that arises only when an entity is considered as a whole and it cannot be fully comprehended only by the properties of its parts (Flood, 2010).

Telecoupling studies build upon the conceptual frameworks of coupled human-environment systems (Turner et al., 2003), socio-ecological systems (Folke et al., 2005; Young et al., 2006a and 2006b) and coupled human and natural systems (Liu et al., 2007) adding to these the emphasis on the distant interactions between systems (Liu et al., 2013). Coupled systems are characterized by complex interactions of socioeconomic and biophysical elements that impact each other in dynamic, nonlinear and emergent ways (Friis and Nielsen, 2016; Liu et al., 2007). The scale of the place-based coupled systems can vary from local landscapes to global regions in nested hierarchy allowing the analysis for different spatial and temporal resolutions (Friis and Nielsen, 2016).

This study follows a structured telecoupling approach, where two systems are separated by spatial distance, most commonly by country borders. The approach presents a comprehensive systemic framework proposing an analytical tool to study the telecoupling components and their interactions with others (Friis et al., 2016; Liu et al., 2013). Telecoupled systems are seen as hierarchical and they can be classified as sending (the systems from where the flows move outward), receiving (the systems that receive the flows from the sending systems) or spill-over systems (the systems that impact and/or are impacted by the interactions between the sending and receiving systems) (Liu et al, 2013). Areas can also act simultaneously as sending, receiving or spill-over systems (Liu et al., 2013). In this thesis, the main focus is on the interconnections between the sending and the receiving systems, and the system boundaries are marked by country borders.

The demarcation of system boundaries in structured approach is criticized and can be seen as problematic, because areas are interconnected with socio-economic, biophysical and historical connections, therefore making the framing decisions always somewhat arbitrary (Friis et al., 2016). Heuristic approach, an alternative approach in telecoupling research (Friis et al, 2016), adds to this by stating that also for example different governance systems creates a separation (Eakin et al., 2014). Therefore, according to the heuristic approach, social and functional distance in terms of governance are equally important.

Proximate causes describe the local, immediate causes of land use change and underlying driving forces the broader more complex relations behind them (Friis et al., 2016). Concepts of e.g. *displacement* (actions in one place causing sometimes unexpected migration of activities to another place and the related land use change), *rebound* (a response of agents or systems to measures introduced to reduce the resource use) and *cascade effects* (a chain of effects caused due to a change in system in one place) have been applied to describe these kind of complex interactions between telecoupled areas (Lambin & Meyfroidt, 2011; Meyfroidt & Lambin, 2009).

2.3. Methodological framework

To study the telecouplings and the displaced environmental impacts embedded in food trade, a physical accounting approach was adopted. Methodologically, the approach leans on the research field of industrial ecology that focuses on the flows of material and energy and the effects of these flows on the environment as well as the influences of political, economic, regulatory and social factors on the resource use (Allenby, 2006; White, 1994). The field was created in the early 1990s in response to a need for a more transformative research that aimed to close the energy and material use loops and reduce the environmental impacts of industrial systems that were to be analyzed together with the surrounding systems, not in isolation from them (Graedel & Allenby, 1995; Graedel & Allenby, 2005). The industrial systems were considered as analogues to natural ecosystems where the material cycles are closed and no material is wasted (Graedel & Allenby, 2003).

Industrial ecology provides many analytical tools, such as material and substance flow analysis, life cycle impact analysis or the input-output analysis that can be very useful also in the context of land system science. The same basic principles of e.g. mass balance hold true for both fields: no material is lost, but instead they can be transformed and mixed in processes and flows between systems.

In this research, the basic ideas of material flow analysis are applied in the physical accounting of agricultural trade flows between countries. These models are based on the information on the production, imports, exports and domestic utilization of the commodities from the agricultural and forestry statistics (Bruckner et al., 2015; Kastner et al., 2014a). An alternative approach to study the material flows in international trade would be to use environmental-economic accounting models that are based on the tracking of monetary transactions between the sectors and countries and this way study the embodied land flows through the economy (Bruckner et al, 2015). However, in this research the physical accounting method was followed because of the greater detail in agricultural commodities analyzed compared to the many environmental-economic models and the allocation logic of tracking embodied land use along actual physical commodity flows. The focus was on the crops and animal products traded between countries.

3. Materials and Methods

In this thesis, the displaced pressures of food consumption through international trade were analyzed with a focus on the Finnish food consumption and trade in Papers I–III and on the EU countries in Paper IV. The displacement of environmental pressures were analyzed with different indicators including land use (Papers I and II), water use (Papers II and III), greenhouse gas footprints (Paper IV) and the biodiversity impacts related to the resource use (Paper II). Also, the potential to reduce the displaced water use by replacing the imports with domestic production was analyzed (Paper III). The focus of the Paper IV was on the development of greenhouse gas footprint accounting framework integrating the analysis of international food trade in it. The analysis methods used in the research articles are described here briefly, but for a more detailed explanation please refer to the original publications.

3.1. National level food supply

The data for the country level quantities of food imports and exports and national food supply was based on the statistics of the Food and Agriculture Organization Food Balance Sheets (FAO FBS) (FAO, 2018). This database includes information about the crop and animal product consumption and their imports and exports. It also provides data of the country level food supply divided in different product groups.

While FAO FBS is probably the best suited database for this kind of global scale analysis, its use is related with a number of limitations and inaccuracies. The quality of the data vary among countries and products, because of differences in country-level statistical systems and data reporting (FAO, 2001). The basic data for FAO FBS sheets is gathered from various data sources such as direct enquiries, surveys, records or estimates of government agencies sometimes with differing temporal coverage, and therefore, they are subject to inconsistencies (FAO, 2001). However, these inconsistencies are generally lower in highly developed countries such as Finland, compared to the many developing countries.

The products included in the study were crops (Papers I–IV) and animal products including cattle, pork and poultry meat, dairy and eggs and the products processed from them (Papers I and IV). Fish and other seafood, offal, and animal fats were excluded from the analysis. The product groups covered in this study include on average 95% of the food supply in the EU countries (FAO, 2018). Paper I had the largest time scale analyzing the agricultural trade from 1961–2007. Papers II and III focused on the years 1986-2011 and the focus on the Paper IV was on the consumption for the year 2010.

Feed use and the pasture area related to animal feeding was analyzed with different methods. In Paper I, the feed embedded in the imports and exports of animal products was calculated based on the proportions of different crops in the animal feed from Wirsenius (2000) and the annual pasture area from Ramankutty et al. (2008) based on the total amount of grass needed. In Paper II and III only the crop imports into Finland were assessed including the crops used as feed using data from Kastner et al. (2014a). This data was based on the national level food supply and feed use data from FAO (2018). In Paper IV the feed use and pasture area used were based on the coefficients from Herrero et al. (2013), providing feed requirements for 30 world regions which were furthermore mapped to country level for our analysis. Aggregated feed requirements per production system were distributed into individual crops, such as oil crops to rapeseed and others, based on feed crop consumption statistics (FAO, 2018). Feed use numbers from Herrero et al. (2013) were rescaled to national-level feed use totals in FAOSTAT 2009–2011 (FAO, 2017) for consistency. In Paper IV feed crop emissions were accounted as part of the consumption emissions of animal products.

3.2. Land use embedded in the Finnish agricultural trade 1961-2007 (Paper I)

The framework used for the accounting in Paper I is presented in the Figure 1. Finnish agricultural trade (FAO, 2018) was connected to land use identifying the trade partners from COMTRADE (2013). Land use was analyzed taking into account the cultivation areas for crops and the area required for feed embedded in the animal products (Fig 1).

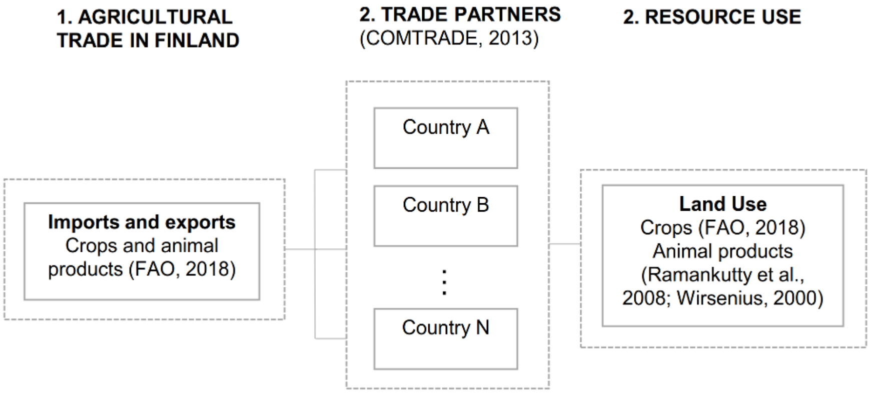

Figure 1. Framework for the impact accounting used in Paper I. Principal data sources are presented in parentheses.

The quantities of crops and animal products traded were transformed into quantities of land used. For this, country level data of annual crop yields in the exporting country were used from FAOSTAT (FAO, 2018). Land use embodied in imports is referred as gross displacement and the land use embedded in exports as gross absorption, following the terminology used in Meyfroidt et al. (2010). The difference between these two is called net displacement of land use demand, or in the case this is negative it is called net absorption.

3.3. Land and water use and the biodiversity threats embedded in the Finnish crop imports (Paper II)

In Paper II the food supply in Finland was connected to global crop trade analysis from Kastner et al. (2014a) and to land and water use in the production areas (Fig 2). These were later multiplied with the biodiversity characterization factors to estimate the impacts of Finnish food supply to global biodiversity loss at species level (Fig 2).

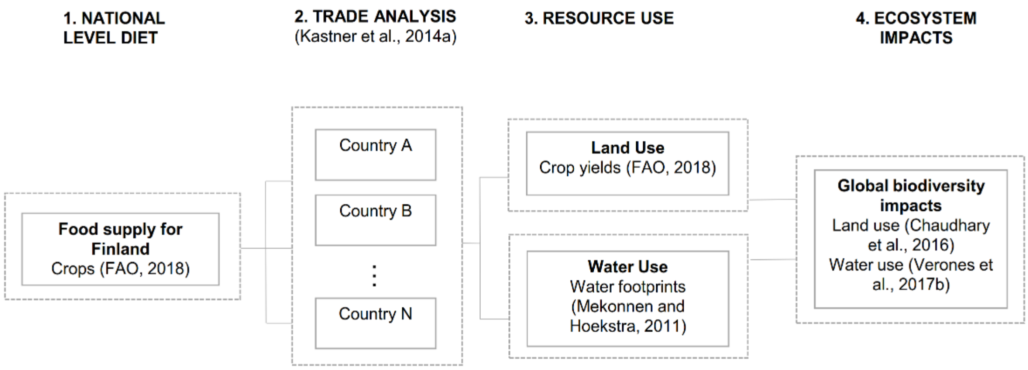

Figure 2. Framework for the impact accounting used in Paper II. Principal data sources are presented in parentheses.

For the impact accounting, it is important to trace back the production country of a food commodity, because although value is added throughout the whole supply chain, the biggest impacts related to resource use are caused in the primary production (Kastner et al., 2011). However, especially in food sector, this is not always an easy task to do. Raw materials with different origin are often mixed in consumer products and food commodities traded internationally are many times re-exported between various intermediate countries before ending up in the consumer's plate. National statistics usually report only the country where the last value was added to the product. This way, for example, in the trade statistics of FAO (2018) the Netherlands was the biggest soybean cake importing country to Finland in 2010, although the Netherlands does not produce soybeans in industrial quantities, but instead only re-exports them further.

Therefore, in Papers II–IV, the methodological approach and data from Kastner et al. (2014a) was applied for tracing of the primary production countries. This data provides information about the national level food consumption (crops and animal products) and their primary production countries. The material flows were traced through the whole supply chain using an accounting system that is based on the assumption that imports and domestic production contribute in proportional shares to a country's consumption. To put it into an example: if food consumed in country A is imported from country B but actually produced in countries C and D, the countries C and D should be linked with the consumption of the country A in proportional shares.

The quantities of crops imported were converted into hectares of cropland using country- and crop-specific yield data, similarly as in Paper I. However, there is a difference between the land use accounting frameworks between Paper I and II because of the difference in the trade flow analysis followed. Paper I accounted for the land use using yield data for the exporting country presented by the national statistics (COMTRADE, 2013), whereas Paper II used the yield data for the production country identified with the trade flow analysis from Kastner et al. (2014a). Furthermore, the accounting framework used in Paper I included the grasslands used as pasture, while this was excluded in Paper II.

In Papers II and III also the virtual water quantities embedded in the crop imports were analyzed. Virtual water refers to the sum of quantities of water resources used in the production processes of a good (Hoekstra, 2003). The use of water resources can be divided into the three "colors" of water representing different sources and dynamics of water use expressed in water volume per unit of product (usually m^3 ton^{-1}). Blue water refers to the quantities of surface and groundwater used, whereas green water refers to the amount of rainwater consumed (Mekonnen and Hoekstra, 2011). Therefore, green water use is closely related to the land area used. Grey water is an indicator of water pollution and it refers to the amount of water required to assimilate pollutants to meet water quality standards (Mekonnen and Hoekstra, 2011). In this thesis, only the green and blue water use were analyzed. Although water pollution due to human activities is a growing threat, its accounting method is still debated, and includes a lot of uncertainties (Hoekstra, 2016), and therefore in this analysis, grey water was excluded.

The quantities of crop imports into Finland were transformed into quantities of green and blue water used in the production areas. This was done using country- and crop-specific water use coefficients from Mekonnen and Hoekstra (2011). Virtual water embedded in crop imports were accounted for Finland for 1986–2011. Water use was accounted only from the primary production and we did not account for the water use from the processing, packaging or transportation of crops. The water use coefficients from Mekonnen and Hoekstra (2011) are calculated as the average use of 1996–2005. Therefore, the temporal dynamics of water use efficiency changes could not be considered. Crops imported were multiplied with water use coefficients to analyze the water use embedded in crop imports.

In addition to land and water use, also the impacts of these uses to species richness were analyzed. Biodiversity entails many levels (e.g. genetic, individual, populations, species, and ecosystems) that all deserve detailed analysis. However, in this research the focus was only on the pressures on species level, although acknowledging that these pressures impact on more than one level (Winter et al., 2017). There are various methods that can be used to account for the biodiversity impacts related to certain resource use (Gabel et al., 2016; Winter et al., 2017). Many of these biodiversity characterization factors have been developed to be used in the life cycle assessments (LCA) and they typically focus on the species or ecosystem levels (Winter et al., 2017). The characterization of biodiversity usually includes the spatial analysis and modelling of e.g. species richness and the threats to them related to different resource uses (e.g. land, water, greenhouse gas emissions, eutrophication) (Winter et al., 2017).

In Paper II the biodiversity impacts were analyzed with two methods: characterization factors for global species diversity impacts for 1) land use from Chaudhary et al. (2016) and 2) for water use from Verones et al. (2017b). These approaches were applied because of their global applicability. The characterization factors for land use were based on countryside species-area relationships (SARs) analyzed for four animal classes (mammals, birds, amphibians and reptiles) (Chaudhary et al., 2016). The characterization factors for water use (from Verones et al., 2017b) were combined from two methods: the first one assesses water consumption impacts to wetland area loss also analyzing four animal classes (Verones et al., 2013), and the second one focusing on water consumption from the share of water limited net primary productivity for terrestrial plant species (Pfister et al., 2009). An estimate of the global biodiversity loss was calculated multiplying the resource use with characterization factors that describe an impact per resource use. The loss was expressed as the global potentially disappeared fraction of species in a year (gPDF a). The application of the global biodiversity characterization factors was chosen to highlight the impacts of consumption in areas hosting a high number of threatened and endemic species (Chaudhary et al., 2016). In the approached applied, global biodiversity refers to species number, threat level and share of geographical range of species at a certain location. Since different approaches and taxa were used to derive the characterization factors for land and water use, they are not necessarily compatible and cannot be directly compared, but each can give valuable information on their own.

3.4. Replacing crop imports with domestic production to reduce virtual water imports (Paper III)

The accounting framework for Paper III is presented in Figure 3. First, the virtual water imports into Finland related to the crop-based commodities were analyzed similarly as in Paper II. In addition, also the water scarcity in the production was analyzed. Later, the most important products imported into Finland from the regions suffering from water scarcity were analyzed and three primary crops – rice, soybeans and rapeseed – were selected for a closer analysis. The potential to replace the imports with domestic production was analyzed and the regions from where the water imports would be reduced were identified.

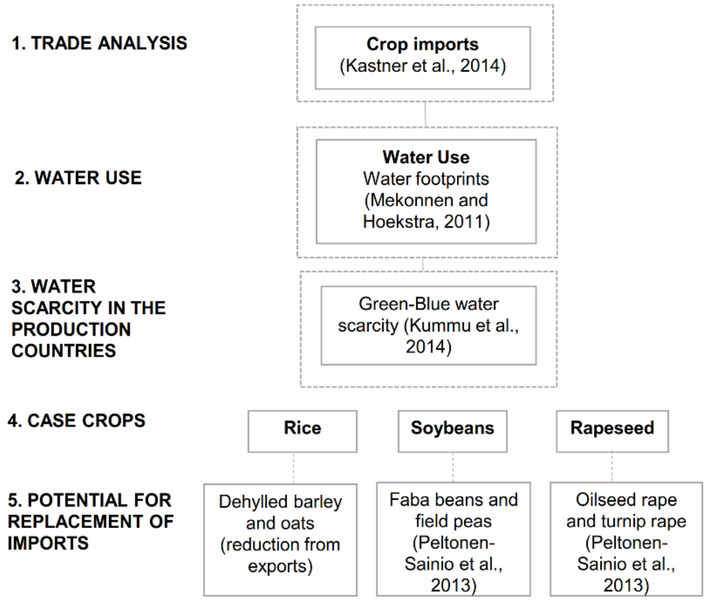

Figure 3. Framework for the accounting used in Paper III. Principal data sources are presented in parentheses.

First, the analysis of water use embedded in the Finnish crop imports from 1986 to 2011 proceeded as in Paper II, but this time, both green (e.g. the rainwater) and blue (e.g. surface and groundwater) water use were analyzed. The most important products imported to Finland were identified in the light of their contribution to virtual water imports embedded in the Finnish crop imports, and three products, rice, soybeans and rapeseed were chosen for a closer examination. The data of green-blue water scarcity in the production areas was applied from Kummu et al., (2014) to analyze water scarcity in the production areas.

Next, the potential to use domestic production of the same or substitute crops to replace their imports was analyzed. Rice is not adapted to Northern climatic conditions and hence it cannot be cultivated in Finland. Therefore, dehulled barley and oat grains were considered as potential alternatives due to their use in the Finnish cuisine in place of rice. However, because Finnish crop rotations suffer already from barley and oat monocultures (Peltonen-Sainio et al., 2017) the expansion of their current cultivation areas were thus considered unsustainable. The capacity to replace rice with barley and oats was therefore considered only by reducing their exports. With soybeans, the Finnish substitute crops were considered to be faba beans and field peas. Rapeseed imports were considered to be replaced with the increase in domestic oilseed rape and turnip rape production in Finland. The theoretical potential of the expansion of legume and rapeseed cultivation in Finland was based on the study of Peltonen-Sainio et al. (2013) taking into account regional production risks and rotation requirements. The expansion of legumes was considered to take place in the current cereal cultivation fields, this way also contributing to the diversification of currently cereal-dominated Finnish agricultural landscape. Finally, the quantities and regions were identified, where the water use would be reduced if all the potential for substituting rice, soybeans and rapeseed imports with domestic production would be harnessed in Finland.

3.5. Accounting of the dietary greenhouse gas footprints (Paper IV)

In Paper IV the environmental impacts of food consumption were analyzed with greenhouse gas (GHG) footprints. GHG footprint is an indicator of the greenhouse gases emitted during the production and transportation of a good. The GHGs included in the analysis were carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The CH_4 and N_2O emissions were converted into CO_2 equivalents using global warming potential values (with a 100-year time horizon) of 25 and 298, respectively (Eggleston et al., 2006).

The trade flow analysis data from Kastner et al. (2014a) applied also in the Papers II and III was incorporated into the GHG emission accounting, therefore being able to use country- and product specific emission factors in the accounting (Fig 4). The main sources of GHGs related to agricultural production were accounted for, including inorganic and organic fertilizer use, rice cultivation, and livestock production containing enteric fermentation, manure management, and emissions from manure left on pastures. Additionally, also the deforestation and peatland cultivation emissions caused by land use change were analyzed together with rough emissions estimates from international transportation (Fig 4).

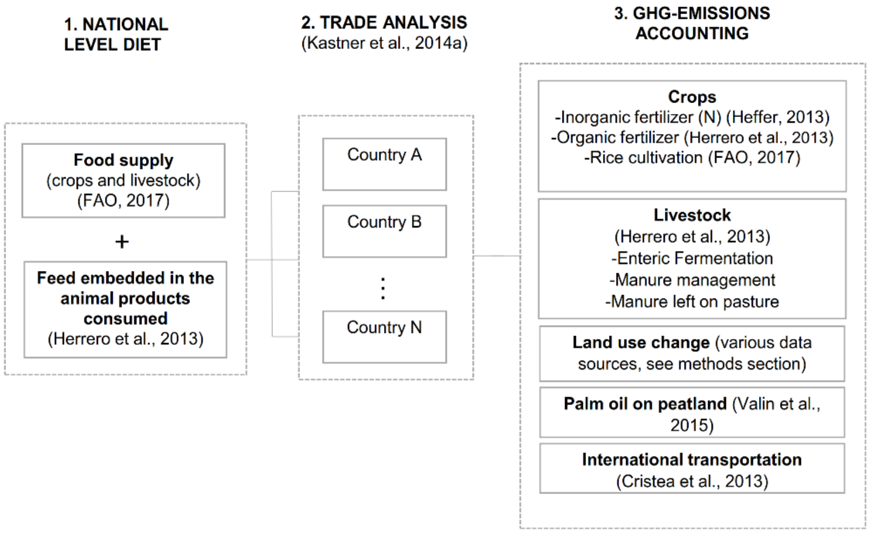

Figure 4. Framework for the dietary emissions accounting used in Paper IV. Principal data sources are presented in parentheses.

For the direct and indirect GHG emissions caused by inorganic nitrogen fertilizer use, data from the International Fertilizer Association was used (Heffer, 2013). The data constitutes of information on country-level fertilizer use in 2010−2011 that were further divided by total harvested area (FAO, 2018) to obtain the crop- and country-specific nitrogen fertilizer use per area. These numbers were rescaled to match countries' total nitrogen use levels from FAO (2018). Organic fertilizer use was based on the data from Herrero et al. (2013). Methane emissions from rice cultivation were calculated using emission factors from FAO (2018).

Livestock related emissions cover direct emissions from production and indirect emissions from feed cultivation. The emission factors were retrieved from Herrero et al. (2013) analyzing emissions from enteric fermentation, manure management and emissions from manure left on pastures.

To account for the land use change (LUC) emissions, a simplified top-down accounting method was applied. It distributes emissions at the country level to cropland and pasture. First, the deforestation emissions in each country (FAO, 2018) were multiplied by the share of deforestation attributed to commercial and subsistence agriculture (Hosonuma et al., 2012). To account for the fluctuation of the land use expansion patterns, the average emissions for the period 2002−2011 were used. These numbers were multiplied with the relative contribution of the crop or pasture expansion of the total agricultural expansion in a country (FAO, 2018), only taking into account crops and pasture area that had expanded their harvested area. Finally, the emissions were divided by the area of cropland or pasture in a country in 2011. The method used was based on the indirect approach, allocating emissions to products based on their relative share of agricultural land expansion. This method, therefore, puts more weight on the underlying causes of deforestation, in contrast to a direct approach that would allocate the emissions directly to the activities that take place in the deforested area (Cuypers et al., 2013; Persson et al. 2014).

Also, emissions from land use change emissions from organic soil from palm oil cultivation were analyzed. A substantial share of palm oil plantation expansion has occurred on peatland (Gunarso et al., 2013). When soil is drained, the peat decomposes releasing greenhouse gases even for decades. Malaysia and Indonesia are the largest palm oil producers, and together produced over 80% of global production in 2011 (FAO, 2018). Therefore, only the emissions from cultivation on organic soils from these countries were analyzed, using an emission factor of 61 t CO_2 ha^{-1} yr^{-1} (Carlson et al., 2017; Valin et al., 2015), multiplied with the share of palm oil cultivation on peatland (Gunarso et al., 2013), to get the emission factors for an average palm oil ton produced in a country.

In addition to the pre farm-gate emission sources, also the emissions from international transportation were estimated. A simplified approach was used, assuming that all agricultural trade from outside Europe is transported by sea, either as bulk or container cargo, and enters Europe through the port of Rotterdam. This port was chosen due to its importance and central location. The distance travelled was multiplied with the per ton-km emission factors from Cristea et al. (2013) for different transportation modes.

4. Main results

4.1. Increased outsourcing of land and water use

Both the imports and the exports of the Finnish agricultural commodities have increased in the past 40 years (FAO, 2018). The crop quantities imported more than doubled from 1960s (~ 800 000 tons) to 2013 (~2 350 000 tons) (FAO, 2018). An even more drastic increase can be observed with the imports of animal products that grew more than seven-fold from 22 000 tons in 1961 to 190 000 tons in 2013 (FAO, 2018). The exports of the Finnish agricultural products have also increased following similar trends as the imports.

When analyzing the development of the Finnish food trade in embedded land use, the increasing trend is smoother compared to the increase in quantities. This is mainly due to production efficiency increases. For example, the world average wheat yield almost tripled from 10900 hg/ha in 1961 to 29700 hg/ha in 2010 (FAO, 2018). The gross displacement (imports−exports > 0) impact of crop products in Finland dominated the balance with approximately 700 000 ha in 2007, referring to that in the end of the study period Finland imported more cropland than it exported (Paper I). The increasing trend in both the land imports and exports can be observed especially after the year 1990 (Paper I).

The total demand of cropland for the Finnish food consumption from 1987 to 2011 remained relatively stable as the increases in productivity matched the changing demand due to population growth and consumption changes (Paper II). However, the share of imported cropland embedded in the Finnish food supply nearly doubled from 23% in 1987 to 41% in 2010, calculated in three-year means around the respective years (Fig 5). The land use embedded in crop imports in 2010 corresponded to a cultivation area of about 600 000 ha abroad (Paper II). In 1986 approximately 12% of the calories from crops and 2% of animal products were based on imports, while in 2011 the numbers were 35% and 28% respectively (Paper II).

The spectrum of partner countries diversified over time (Paper II). In 2010 the main crop exporters to Finland were other European countries as well as South America that accounted for over 24% of the total cropland imports in 2010. The imports from other European and Former Soviet Union countries increased from 49 000 ha in 1987 to 284 000 ha in 2011.

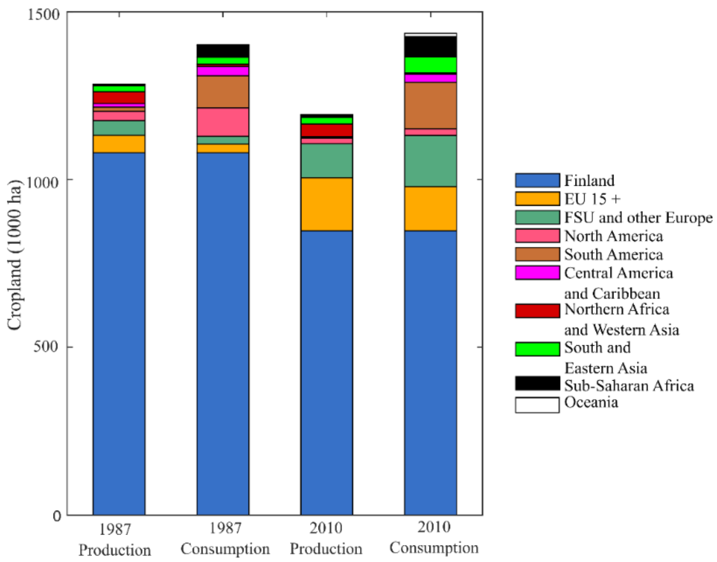

Figure 5. Use of domestic and foreign cropland in the Finnish food supply. Production perspective refers to the area of domestic cropland used for domestic consumption and exports. Consumption perspective refers to the area consumed from domestic production and imports. Results are presented as three-year means around the respective years. (Paper II)

The main import crops have varied in time with the exception of coffee, which has annually required a cultivation area of about 100 000 ha from 1960s to 2010s (Papers I and II). Wheat was one of the main imported products in terms of land use in the early 1960s but since then, its imports have varied depending on the success of domestic wheat production in Finland. Also soybeans have been among the most important import crops to Finland (Fig 6). The variety of import items increased over time. The three most important import crops covered 45% of all imports in the 1960s, while their share in the 2000s was 32% (Paper I). The highest increase in the Finnish crop imports was with crops that could also have been cultivated domestically (Paper II). The imports of crops that due to climatic restrictions could not be cultivated in Finland, remained relatively stable.

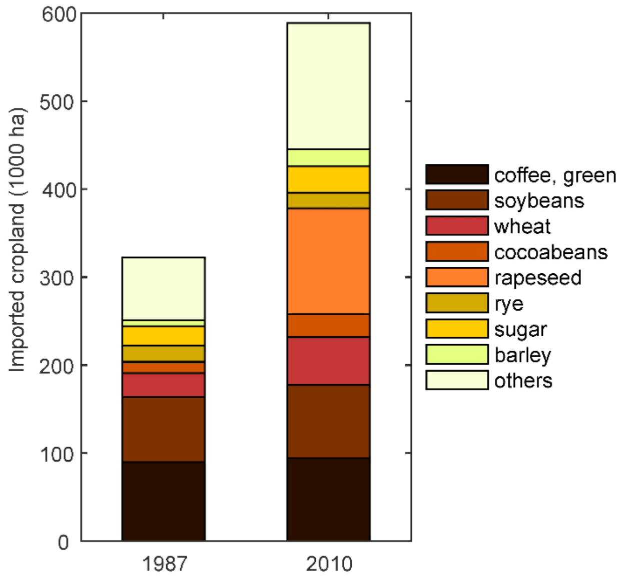

Figure 6. Imported cropland to Finland by crop type. Results are presented as three-year means around the respective years.

In the 1960s Finland was nearly self-sufficient with the meat and dairy production, when considering only the direct consumption. However, in the 1980s the imported beef and pork products entered the Finnish market, and by the end of the study period covered the largest share of the animal product imports.

Also the gross absorption, i.e. the impact of Finnish export trade, increased reaching a level of 300,000–500,000 ha in the 1990s (Paper I). Cereals dominate the Finnish crop production (Peltonen-Sainio et al., 2017) and wheat, barley, oats and rapeseed oil were the most important exported crop items in terms of land use. Wheat remained important in the 1960s and 1970s. Later, barley and oats increased their share in exports. After 1995, the three most important exports crops were consistently barley, oats and rape oil. Dairy products dominated the land use related to exports of animal products in the early 1960s while in the 2000-2007 the dominant product was pig meat (Paper I).

Table 2. Land and blue water use of the Finnish crop consumption by domestic production and importing regions. Numbers presented as three-year means around the respective years.

	Land use				**Blue water use**			
	1987		**2010**		**1987**		**2010**	
	(1000 ha)	**(%)**	**(1000 ha)**	**(%)**	**(1000 m^3)**	**(%)**	**(1000 m^3)**	**(%)**
Finland	1080	77	847	59	8865	7	9711	8
EU 15 +	26	2	131	9	18518	15	42367	36
FSU and other Europe	23	2	153	11	2245	2	3182	3
North America	85	6	20	1	32593	27	9994	8
South America	95	7	139	10	8783	7	14783	13
Central America and Caribbean	28	2	24	2	2862	2	2204	2
Northern Africa and Western Asia	7	0	4	0	24291	20	6449	5
Sub-Saharan Africa	35	2	61	4	12062	10	8980	8
South and Eastern Asia	21	1	48	3	5180	4	19374	16
Oceania	3	0	9	1	7339	6	726	1
Total	**1403**		**1436**		**122738**		**117770**	

The differences in the scope and methods of identifying the production country for the imported products between the Paper I and the rest of the Papers in this dissertation resulted also in differences in the results. Paper I presented on average greater agricultural land imports compared to Paper II. In Paper I the agricultural land imported between 2003 and 2007 was 680 000 ha while in Paper II the number was 530 000 ha. The differences between the two results are mainly explained by two aspects. First, the accounting framework presented in Paper I, included also pasture in addition to cropland area. Second, the cropland areas in Paper II are accounted using crop yield data from the production country identified with the trade flow analysis (Kastner et al., 2014a) while Paper I relied only on the trade data from national statistics (COMTRADE, 2013). However, the general trends in increasing imports were found similar in both papers. Because of the re-exports between countries, that were not accounted for in the Paper I, the method proposed by Kastner et al. (2011 and 2014a) adopted in Papers II-IV can be considered more accurate and the use of these kind of trade flow analyses is encouraged in future studies.

In the high-latitude humid climate in Finland irrigation need is very low and most of the cultivation is rainfed. Therefore, in the domestic crop production the consumption of blue water (= surface and groundwater) is very small, less than 10% of the blue water consumption related to the Finnish crop supply. Annually, Finland imports approximately 100 million m^3 of blue water through the trade of crop-based commodities (Table 2) (Papers II and III). Total blue water imports did not increase much from 1987 to 2010 (Paper III). In 1986 Finland imported blue water embedded in crop imports mostly from other European countries, North America and Western Asia (Paper II). In 2010 other European countries became dominant contributing to approximately 40% of the blue water imports into Finland. Also South America and South and Eastern Asia increased their share in blue water imports. The biggest products contributing to the blue water embedded in the Finnish crop imports were rice, coffee, fresh fruits, oranges, soybeans and mandarins that together in 2011, these six products accounted for over 45% of all blue water embedded in crop imports into Finland (Paper III). The products ranked highest because of a combination of high consumption of blue water in the primary production and also due to large import quantities to Finland.

When comparing the quantities of blue and green water imported, green water dominate the picture. Approximately 96% of the total virtual water embedded in the crop imports into Finland 1986–2011 was green water and only 4% blue water (Paper III). Green water, or the rainwater used in crop production, more than doubled from 1200 million m^3 in 1986 to 2600 million m^3 in 2011. In the same period, the population in Finland increased from 4.9 million to 5.4 million (FAO, 2017) that can partly have contributed to the increased imports. The products with the most green water imports into Finland in 2011 were coffee, soybeans, rapeseed, wheat, palm oil and cocoa beans contributing together for 77% of the total green water imports analyzed (Paper III). The green water imports from other European countries increased from 6% to almost 30% during the past 30 years. Latin America has, however, remained the most important green water import region to Finland, contributing 30%–50% of the green water imports from 1986 to 2011 (Papers II and III).

4.2. Biodiversity impacts of the Finnish food consumption

Environmental impact assessments should go beyond just accounting for the pressures from the resource use and actually analyze how this resource use affects ecosystems (Verones et al., 2017a). Therefore, in Paper II we analyzed how the displaced land and water use of the Finnish food consumption has affected global biodiversity.

Finland is a country with low endemic species richness (Kier et al., 2009). Therefore, over 93% of the biodiversity impacts related to land use (measured as potentially disappeared fraction of global species richness caused by the Finnish food consumption) took place outside the Finnish borders. The most severe biodiversity threats caused were related to crop imports from Brazil, India, Colombia and Indonesia (Fig 7). When taking a closer look at the individual crops, the highest ranked were coffee, cocoa, sugar, rubber and soybeans.

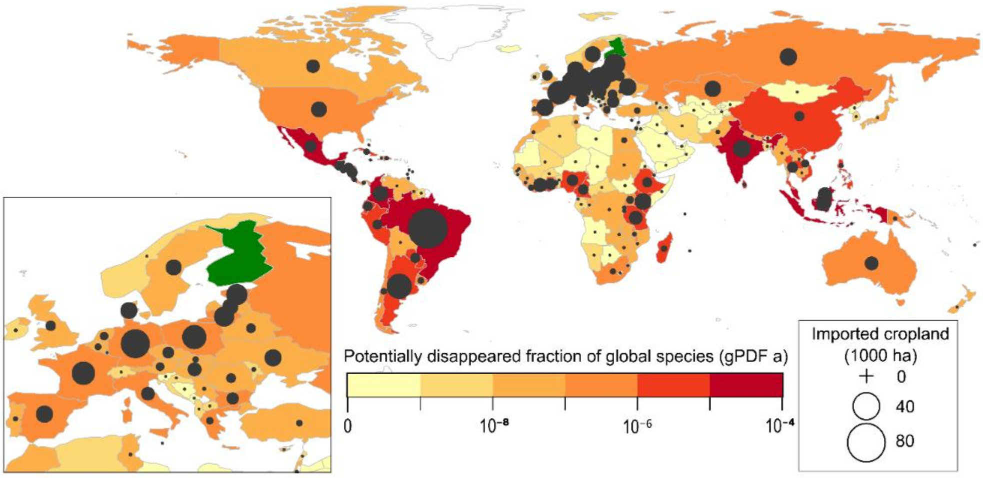

Figure 7. Cropland embedded in the Finnish food imports and the impacts on global biodiversity in 2010. Bubbles present the "imported" cropland and the colour of the countries represents the biodiversity threats caused the cropland use.

When applying another indicator, in this case blue water use, the picture is somewhat different (Fig 8). Over 99% of the biodiversity impacts caused by Finnish food consumption related to blue water use took place outside Finland. Rice and citrus fruits from Spain, USA and Egypt ranked the highest when analyzing the individual crop and country combinations.

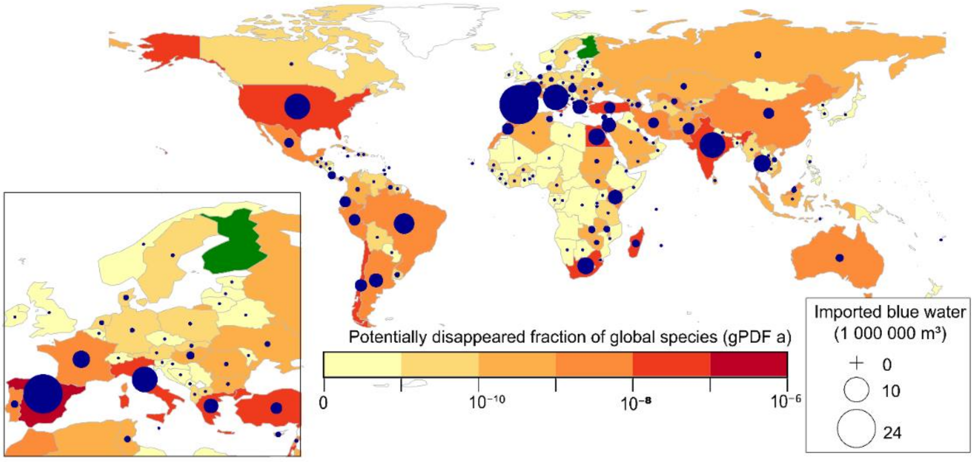

Figure 8. Blue water embedded in the Finnish crop imports and the impacts on global biodiversity in 2010. Bubbles represent the quantities of blue water "imported" and the colour of the countries represents the biodiversity threats caused by blue water use.

Box 1. Environmental concerns related to some food commodities imported to Finland

Beef and dairy –Ruminant meat and dairy production have higher carbon footprints compared to most plant based products and many other animal products and they contribute to 21% (beef) and 30% (dairy) of the GHG emissions of an average Finnish diets. They require also high amounts of land and water resources both directly and indirectly due to feed production. More than 80% of the beef and dairy consumed in Finland in 2010 was produced domestically. Most of the imports came from proximate countries such as Germany, Poland and Sweden.

Coffee – Finnish people are among the thirstiest coffee drinkers in the world, with an average per capita consumption of 12 kg per year, compared to world average 1 kg per year. In 2010 coffee was imported to Finland mainly from Brazil, Colombia, Guatemala and Kenya. Coffee imports contribute to18% of the cropland, 9% of the blue water and 36% of the green water embedded in the crop imports into Finland.Their production was found to be related to some of the highest biodiversity threats related to the Finnish food consumption.

Rapeseed – Rapeseed is imported to Finland mainly from Germany, Kazakhstan, Estonia and Latvia. The increase in the land embedded in rapeseed imports into Finland has been particularly high. In the late 1980s less than 1000 ha of rapeseed was imported to Finland, while in 2010 the respective number was already more than 100 000 ha. In 2010 rapeseed imports contributed to 22% of the cropland and 15% of the green water embedded in the crop imports into Finland.

Rice – Rice is imported to Finland mainly from Spain, Pakistan, India and Italy. Water footprint of rice is high compared to most other staple crops and it has been related to the overuse and depletion of groundwater resources in many parts of the world (Dalin et al., 2017). Although rice consumption in Finland is quite low compared to global average, in 2010 the rice imports contributed to 16% of the blue water imports embedded in the crop imports into Finland. Rice production is also an important source of methane which is a powerful greenhouse gas. Rice imports into Finland are related to high water use related biodiversity threats displaced by the Finnish food consumption.

Soybeans – Soybeans are imported to Finland from the USA, Brazil and Argentina mainly for animal feed (Peltonen-Sainio et al., 2013; Peltonen-Sainio and Niemi, 2012). The most common concern related to soybean production is its role as a driver for tropical deforestation especially in South America (see e.g. Arima et al., 2011), and therefore soybean production from the deforested areas have also high land use change emissions contributing to climate change. Soybeans contributed to 13% of the cropland and 14% of the green water embedded in the crop imports into Finland in 2010, and ranked also among the highest causes of biodiversity threats related to the consumption in Finland.

Tropical fruits – Many tropical fruits are produced in regions with high species richness. Therefore, the use of resources such as water or land in their production can create competition with other users e.g. ecosystems in the area. For example, cocoa imports are related to some of the highest threats caused by the Finnish land use imports. In 2010 the biggest exporters of cacao to Finland were Cameroon, Ecuador, Ivory Coast and Nigeria. Some tropical fruits, such as oranges and mandarins have high water footprints and they are also produced with areas that need irrigation. Oranges and mandarins are imported to Finland e.g. from Spain, Egypt and Morocco that suffer from problems with water scarcity. The imports of these fruits are related to high water use related biodiversity threats caused by the Finnish food consumption.

4.3. Potential to reduce the virtual water imports

In Paper III the focus was on the virtual water imports. Finland is a land with abundant water resources, and yet it imports some water intensive products also from water scarce areas. We chose three crops, rice, soybeans and rapeseed that contributed substantially to the virtual water imports into Finland and analyzed their replacement potential with domestic production of the same or alternative crop.

Nearly all of the imports of the three studied crops could be replaced by domestic production (Table 3). This would reduce the crop related virtual water imports into Finland by 16% (blue water) and 30% (green water). It is important to notice here, that these figures are calculated only considering the water use in the primary production. Water use further in the supply chain was excluded due to difficulties of finding reliable data with global coverage.

Table 3. The potential reduction of annual virtual water imports (BW= blue water, GW= green water) in the case of replacing rice, rapeseed and soybeans with local production.

Imported product	Imports (mean 2009–2011) [t yr^{-1}]	Substitutive domestic product	Potential for substitution [%] *	Reduction of BW imports		Reduction of GW imports	
				[1 000 m^3 yr^{-1}]	% of total [1]	[1 000 m^3 yr^{-1}]	% of total [1]
Rice	25 000	Barley/Oats	100	16 000	14	22 000	0.7
Soybeans	188 000	Field peas/ Faba beans	100	1 800	1.6	380 000	13
Rapeseed	245 000	Rapeseed	98	460	0.4	450 000	16

[1] By total, we refer to the virtual water imported though total crop imports into Finland in the years 2009–2011.

* Theoretical potential.

When considering the impacts of the resource use, the quantities of water use are not as important as the question of where the water use takes place. We found that Finland imports crops also from areas suffering from water scarcity. By replacing the imports of the studied crops with local alternatives, virtual water imports would be reduced from countries such as Spain, Thailand, Pakistan and India that suffer from water scarcity seasonally (Mekonnen and Hoekstra 2016) or throughout the year (Kummu et al., 2010). The estimated blue water saving quantities are relatively small compared to the total amount of water used in the agricultural production in these areas. However, they are not insignificant. The reduction of blue water imports equal annual blue water use of more than 18 000 people when using the water requirement for meeting basic human needs of 1000 m^3 cap^{-1} yr^{-1} from the Falkenmark indicator (Falkenmark et al., 1989). However, the reduction of the exports to the Finnish consumers could be aligned to another country and this could possibly reduce the sustainability gains achieved through the substitution of imports with domestic production in Finland. However, since the demand of staple crops is relatively inelastic (Lambin & Meyfroidt, 2011) it can be argued that the decrease in the outsourced Finnish water footprints would reduce pressure on the environment in the production countries.

4.4. Greenhouse gas footprints of the EU diets

Paper IV focused on the consumption based greenhouse gas footprint accounting related to the food consumption in the EU countries. A novel framework incorporating the material flow analysis from international trade into the emission accounting was used enabling the use country- and crop specific emission factors.

The greenhouse gas footprints of average diets differ considerably between the member countries from 1460 kg CO_2-eq. cap^{-1} yr^{-1} for Portugal to 610 kg CO_2-eq. cap^{-1} yr^{-1} for Bulgaria, with an EU-wide average of 1070 kg CO_2-eq. cap^{-1} yr^{-1} (Fig 9). The largest share of emissions were related to the animal products, especially emissions from enteric fermentation and manure management. International transportation emissions account only for approximately 6% of the total emissions. Non-CO_2 emissions dominate the picture and account on average for over 60% of the total emissions. Emissions related to feed embedded in animal product consumption account for approximately 37% of the total emissions. We found that both total animal product supply and the percentage of emissions outsourced outside the EU region were positive predictors of dietary emissions.

Land use change emissions from deforestation caused by the agricultural expansion are often neglected in the dietary analyses due to lack of consensus of how to account for them. In Paper IV we used a simplified top-down method that allocated the country-level deforestation emissions to the crops and pasture that had expanded their area. Land use change emissions account for on average a third of the dietary emissions and 70% of them were related to feed production, especially soybean.

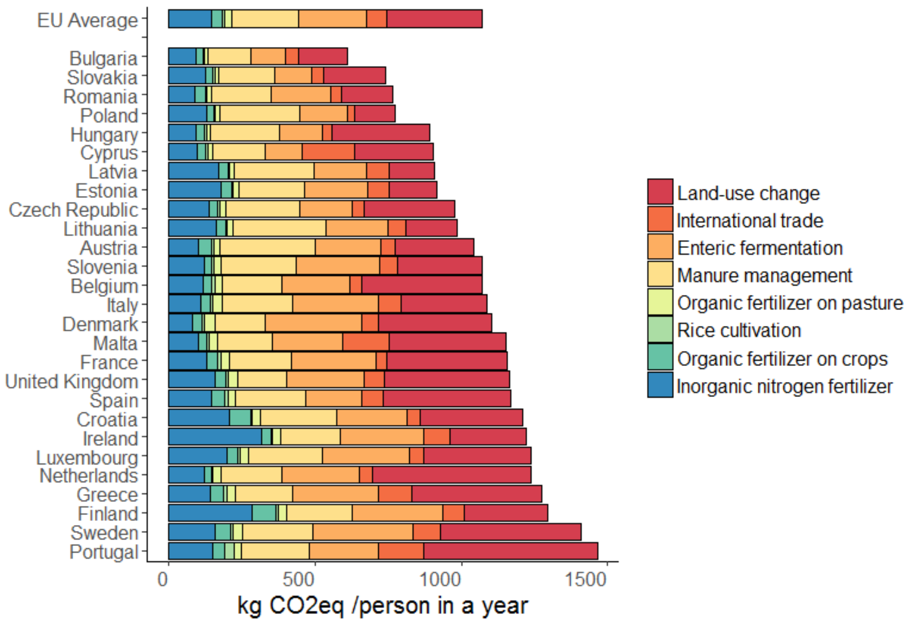

Figure 9. Production- and trade-related dietary greenhouse gas emissions of the average diets in EU countries.

To evaluate the advantages of country-specific GHG footprint accounting, the framework was compared with two alternative no-trade accounting approaches: one that was based on the consumption-based accounting but used global production adjusted average emission factors, and another that was based on production perspective. It was found that neglecting trade, and using only production country based information about food produced in that country, underestimates the total emissions. This is true particularly in countries and regions such as the EU that rely on imports on a substantial share of its food consumption. Production based accounting excludes emission sources related to imported products, such as emissions from international transportation and land use change related to deforestation. Using world average emission coefficients resulted as a relatively good approximation. However, there were differences between the results especially with the shares of different emission sources that could lead to varying interpretation of the results.

Accounting with a production country- and product specific resource use makes it possible to highlight differences in production systems more easily and analyze where interventions make most sense in reducing the negative environmental impacts. It can also improve accuracy and allow a more specific allocation of impact responsibilities from exporting countries to final consumers. This way it is possible to demonstrate the connections and consequences of food consumption in one place to remote processes in another place, such as deforestation in the production countries.

5. Discussion

The main findings of this thesis are in line with the results of previous studies about the increased trends in the Finnish trade and about the importance of taking into account also the material flows and impacts embodied in trade (Hyrylä, 2016; Mattila and Saikku, submitted; Mäenpää and Siikavirta, 2007; Nikula, 2012; Seppälä et al., 2011). Therefore, this thesis confirms and extends previous knowledge considering, for the first time, land and water resources and the related ecosystem impacts embedded in the Finnish food imports using physical accounting (Papers I-III). Furthermore, the framework for greenhouse gas footprint accounting presented in Paper IV contributes to the methodological discussion about how to incorporate trade flows into impact accounting.

5.1. Distant impacts of the Finnish food consumption

The increased trends in the quantities and values of both the Finnish food imports and exports have been previously presented and analyzed in reports about the national statistics (Hyrylä, 2016; OSF, 2018b). In 2012, the biggest import groups, in terms of import value in the food sector were fruits, alcoholic beverages, coffee and cheese (Hyrylä, 2016). Interestingly, when analyzing the imports by outsourced land use instead of import value, the picture changes, and products such as cereals and oil crops emerge as the main products (Papers I-III). Nikula (2012) analyzed the Finnish water footprints including various sectors and found that 82% of the total water footprints are related to production and consumption of agricultural products and approximately half of the total water footprints are embodied in imported products. The papers included in this dissertation have continued this discussion by identifying the main commodities, areas and biodiversity impacts related to the virtual water imports together with an analysis of the potential to reduce some of the negative impacts.

Finland has become strongly connected to global agricultural market. Finland is no exception in this sense but instead rather a characteristic active partner in the economy of the globalizing world. Both the imports and exports of land use embedded in the Finnish agricultural trade expanded during 1961–2011. The fluctuation between years followed the variation in climate and its consequences to the domestic yields. Simultaneously, the Finnish population grew from 4.4 million inhabitants to 5.4 million and the GDP of Finland grew 4.6-fold (OSF, 2018b). The increase in imports was especially rapid in the period of 1986 to 2011, when the cropland embedded in the food imports into Finland almost doubled.

In the same period, also the consumption patterns in Finland changed. The per capita consumption of cereals reduced almost 30% from 1960 to 2011 (OSF, 2017). The consumption of meat more than doubled and the highest increase was observed in the consumption of poultry meat (OSF, 2017). Milk consumption halved but the consumption of cheese increased (OSF, 2017). In the EU countries animal products are often produced domestically or traded from close-by countries and feed crops imported from further away. The self-sufficiency rates in animal-derived products in the EU are high (96% for meat and 99% for fresh dairy products) in contrast to the feed inputs needed in their production (31%) (de Visser et al., 2014). The self-sufficiency rates of soya bean meal is only 3% while it supplies 64% of the protein rich feed materials in the EU (de Visser et al., 2014). Soybean production in the important production regions in South America have been related to problems of land use change impacts such as tropical deforestation (see e.g. Arima et al., 2011).

It should be stressed that using resources from another country is not a problem in itself. International trade can contribute to optimizing natural resources use when production takes place in an area with comparative advantage in terms of production efficiency, technologies or natural capital. Food trade has lowered the need of cropland (Kastner et al., 2014a) and freshwater use globally (Dalin et al., 2012) when, on average, food is exported from more resource-efficient production areas to less resource-efficient consumption areas. This can be analyzed when comparing the current system with a no-trade alternative. However, higher agricultural subsidies in major crop exporters may facilitate land- or water-intensive exports despite lower efficiency (MacDonald et al., 2015). Also, more efficient production systems often contribute to a net increase in consumption, which is a typical example of a rebound-effect (Lambin & Meyfroidt, 2011). Therefore, a decrease in environmental pressures at the global level have not been observed, and OECD countries continue to transfer environmental pressures to the non-OECD countries (Wood et al., 2018).

Local conditions determine the potential for the impacts. For example, European countries are the largest source of cropland embedded in imports into Finland, but since the endemism of threatened species in the EU is relatively low, the highest impacts to global biodiversity loss at the species level are caused by the imports of products from countries such as Brazil, India, Colombia and Indonesia, where the species endemism and also their threats are high (Paper II). The pressures on ecosystems might be higher than the sum of the land and water use related biodiversity impacts analyzed separately due to cascade effects, or lower if both pressures relate to the same species. From the water availability perspective, using the freshwater resources for production of exports in water-scarce regions, such as Spain or Pakistan should represent more of a concern (Pfister et al., 2009) than using the freshwater resources in water-abundant areas, such as Finland. Therefore, replacing the water intensive imports of rice, soybeans and rapeseed with commodities from water abundant production landscapes from Finland could represent a potential solution for reducing the displaced environmental impacts (Paper III). However, it should be taken into account that the crop exports often contribute importantly to the development of the production regions. Therefore, instead of striving for complete reductions, more focus should be put on the production structures and practices used. For example, importing environmentally labeled or certified products could potentially avoid the potential adverse impacts in the most vulnerable areas.

Global trade impacts countries' food security through the increase in food availability, and this way allowing countries to overcome local limits to grow (Porkka et al., 2017). However, it also makes the import-dependent countries more vulnerable to disruptions in global food markets (Seekel et al., 2017). Comparing the numbers of domestic consumption and production, Finnish agriculture can meet consumers' needs rather well (Niemi et al., 2013). The resilience in terms of the biophysical capacities of domestic food production is therefore high (Seekel et al., 2017). However, it is important to remember that domestic production relies on several imported inputs such as fertilizers, fuel and machinery (Niemi et al., 2013). Also, the diversity of local production is an important aspect when analyzing the resilience of a food system, and in Finland this can be a challenge when the cereal monocultures and even cereal species monocultures dominate the agricultural landscapes (Peltonen-Sainio et al., 2017). Such a monotonous crop sequencing has many negative impacts on the sustainability and productivity of agricultural systems (Peltonen-Sainio et al., 2017).

Consuming certain commodities such as coffee, tea, nuts and tropical fruits in Finland will most likely always rely on imported products due to climatic restrictions on domestic agriculture. Yet, the trends in the Finnish trade suggest that also the cultivation of some products that have previously been cultivated in Finland has shifted abroad. The highest increases in the land use embedded in the crop imports were related to crops that can be cultivated in Finland, while the share of crops that cannot be produced in Finland in commercial quantities remained relatively stable. This confirms that the increases in crop imports were not related to the increase in consumption of exotic products, but instead possibly to changes in domestic production. From 1960 to 2011 the domestic cropland in Finland decreased more than 20% from approximately 2 600 000 ha in 1960 to 2 000 000 ha in 2011 (OSF, 2018a). Rapeseed is one of the main crops with a reduced cultivation area in Finland and consequently increased imports. These changes might have been related to variations in climate, the increased infections that have affected the domestic yields and political decisions e.g. related to the use of certain pesticides in the EU (Peltonen-Sainio et al., 2007; Peltonen-Sainio et al., 2016). Yet, a recent study showed that most of the food demand in the Nordic countries could be met with domestic sustainable production also in the future (Karlsson et al., 2017). However, these scenarios required considerable reductions of meat and dairy consumption (Karlsson et al., 2017). This highlights the potential of alternative dietary patterns to reduce substantially the Finnish footprint both domestically and abroad.

5.2. Dietary change

Finland rates among the top countries with the highest dietary GHG footprints in the EU (Paper IV). This is mainly because of the high consumption of animal products, especially beef and dairy, that contribute to the largest share of dietary emissions (Paper IV, see also Audsley et al., 2010; Davis et al., 2016; Foley et al., 2011; González et al., 2011; Hallström et al., 2015; Stehfest et al., 2009). Currently, Europeans consume on average 82 kg of meat and 240 kg of milk products per capita in a year, compared to global average of 42 kg and 90 kg respectively (FAO, 2018). This study confirms findings from earlier studies, that the consumption of animal products is related to increased GHG footprints, higher resource use and potential adverse displaced environmental impacts. Transition to a more plant-based diet reduces also the land and water use (Hallström et al., 2015; Jalava et al., 2014).

However, there are considerable differences between animal products consumed. Enteric fermentation of ruminants (beef and mutton) is one of the largest emission sources. Therefore, the emission intensities of ruminant meat and milk are higher compared to those of meat and eggs from monogastrics such as pork or poultry (Herrero et al., 2013). Bryngelsson et al. (2016) studied the climate change mitigation options in the food sector in Sweden and concluded that reduction of the ruminant sector in the EU is inevitable if the EU climate targets are to be met.

Yet, animal production has also the potential to convert biomass not suitable for human consumption into human edible form. It has been estimated that approximately half of the global agricultural area is devoted to the production of feed and more than half of this land cannot be converted to croplands (Mottet et al., 2017). Therefore, ruminant production will most likely remain an important contributor to food security in many areas of the world, as they transform inedible biomass from grasslands and other marginal lands with low cultivation potential, to human edible nutritionally high quality food (Bradford, 1999). However, almost 90% of global ruminant production, in terms of protein, occurs in mixed systems (Herrero et al., 2013) and therefore are at least partly relying on arable land for their feed production. In Europe cattle production consumes 4–5 times more arable land due to the need for conserved feed in long winters, compared to pork and poultry production (Bryngelsson et al., 2016). Therefore a structural shift in the consumption and production from cattle to pork and poultry production would increase the amount of edible protein produced (Bryngelsson et al., 2016).

The role of cattle grazing in maintaining grassland ecosystems for biodiversity conservation and cultural value, should also be considered (Bryngelsson et al., 2016). This is an emerging issue, especially in Europe. However, the scale of cattle production in Europe is so high that there could be major reductions in production, and still there would be enough cattle for maintaining the culturally and ecologically important grassland ecosystems. In addition, the questions of animal welfare should be carefully assessed. In current production systems, animal welfare is often lower in the intensive pork and poultry production compared to cattle production (Bryngelsson et al., 2016). Focusing on the improvements of animal welfare in pork and poultry production in the EU is therefore increasingly needed.

Also, significant differences exist between crop-based products (Carlson et al., 2017). The substitution of livestock products with vegetarian products, such as tofu, can lead to an increase in protein crop imports, especially soybean. This could also imply an increase in land use change impacts. Also, food with a commonly low GHG emissions, such as fruits, when transported by air, may have emissions as large as some types of meat (Carlsson-Kanyama & Gonzalez, 2009).

Average food consumption in most EU countries is higher than the average dietary energy requirements (FAO, 2015). Therefore, avoiding over-eating and altering food consumption to more closely follow the dietary recommendations of health authorities poses a promising strategy for improving health and also for reducing climate change impacts (Alexander et al., 2017; Aston et al. 2012; Haines et al., 2010; Hallström et al., 2017; Tilman & Clark, 2014). Currently, animal products are an important source of protein and micronutrients for the EU consumers, and the nutritional aspects should be carefully taken into account when preparing policy guidance on dietary changes. However, most of the current EU diets contain excessive proteins and substitution with an overall increase in plant-based products would be an effective and sustainable strategy (Audsley et al., 2010). Also, reducing food losses in all stages of food supply chain is an important strategy to decrease the overall material use and the related impacts in food systems (Alexander et al., 2017; Kummu et al., 2012).

“Luxury” products that do not contribute highly to the nutritional value of a diet, such as sweets, snacks and beverages (e.g. coffee and tea) contribute up to a third of the energy input of the total diet (Carlsson-Kanyama et al., 2003) and have high water and land use impacts consequently causing biodiversity impacts in the production areas (Paper II; Lenzen et al., 2012). Coffee, tea, cocoa and spices account only for 7% of embodied harvested area in global trade, but their production is highly export oriented and up to 69% of their harvested area is produced for exports (MacDonald et al., 2015). Therefore, their consumption can potentially be linked to both negative (e.g. biodiversity loss) and positive (e.g. creating income in production areas) impacts and the sustainability aspects related to their consumption call for a more comprehensive research and consumer awareness.

5.3. Methodological limitations and ways forward

Studies focusing on telecouplings can increase the understanding of the impacts and consequences related to consumption and help to identify leverage points for intervention towards more sustainable land use (Friis & Nielsen, 2017). In this dissertation, system boundaries are formed by country borders, as it is often the case in many place-based structured telecoupling studies (Liu et al., 2015). This is practical, because most of the analysis data is available at national level. However, this system definition creates at least two kinds of problems.

First, countries present considerable sub-national heterogeneity regarding their environmental conditions, land use histories and production systems (Godar et al., 2015 and 2016). This is especially true for large countries, such as Brazil, the USA and Finland. Accounting with a finer scale data would improve the accuracy of the impact accounting as it could better differentiate nuances in the local production systems and land use pathways. High spatial detail gridded models of agricultural production already exist (see e.g. Carlson et al., 2017). However, the difficulty is analyzing trade at sub-national level. Telecoupling studies tracing the physical trade flows also sub-nationally already exist (see eg. Godar et al., 2015 and 2016), but the data for sub-national crop production and trade facilities is not available for all countries and products and the spatial detail may vary across countries (Godar et al, 2016). Therefore the choice of system boundaries is always a balance between depth and scale (Godar et al., 2016). The sub-national tracing of consumption and its link to the sub-national production accounting also remains a task for the future.

Second, country borders are inevitably human constructions and many socio-ecological processes mismatch the governance boundaries (see e.g. Cumming et al., 2006; Friis & Nielsen, 2017). The actors and processes impacting land use are not necessarily located in the same geographical space. For example, urbanization can also be considered as a driver for telecouplings between the increasing urban centers and the rural areas that provide the materials for the growth. Therefore, in land systems science, there is an increasing need for a more heuristic approaches, where the system boundaries are open for empirical investigation (Eakin et al., 2014). Analyzing land systems as human constructs, instead of permanent ontological entities, allows researcher to define what is the system of interest, what and who are the processes creating the telecouplings between different systems and where interventions are most efficient (Friis & Nielsen, 2017).

A general challenge of linking the consumption to production related impacts are the indirect effects of production (see e.g. Godar et al., 2016). This is especially important for sub-national analyses but also relevant for country-level studies. Changes in production, such as increasing land area or interventions to increase the sustainability in one location, may push other production to previously uncultivated lands and/or unsustainable pathways (Meyfroidt and Lambin, 2009). These leakage and displacement effects can thus limit the overall net benefits of sustainable practices, and they also impact the usefulness and appropriateness of e.g. the biodiversity impact indicators such as the ones used in the Paper II. The land use change emissions accounting method used in the Paper IV aims to capture also the indirect effects when the expansion of a production might result in the pushing of another production to the forest frontiers. In the approach adopted the crops that had expanded their cultivation potential had larger emission factors independently from where in the country the expansion had taken place. However, the approach entails also many limitations, for example, if the cultivation of a certain crop would have shifted to forestland but the overall cultivation area would not have changed, this approach would not assign land use change emission to that specific crop. The question of responsibility of the impacts and the linking of these to consumption is not simple, and although huge advances have been made with regards to the methodologies available, the question of indirect effects and their links to consumption based impact accounting remains a challenge.

In the papers included in this dissertation, also the incomplete data coverage limits the generalization of the results. When excluding some product categories from the analysis, important impacts of food consumption are neglected. In this thesis, food consumption was analyzed taking into account crop and livestock products. An important group excluded in the analysis is fish and other seafood. Increase in the fish consumption has caused the depletion of ocean fish stocks (see e.g. Myers & Worm, 2003). Fish farming has been suggested as an alternative for reducing the pressure on wild fish stocks, but often production of carnivorous species requires large inputs of wild fish as feed (Naylor et al., 2000). Some aquaculture systems can also impact wild fish supplies through habitat alteration, wild seedstock gathering and other ecological impacts. Also, protein supplements from soybean meal, cottonseed meal and peanut meal are often used (Naylor et al., 2000), therefore creating a need for land use for the feed production.

The focus of the impact analysis was on land and water resources used and the greenhouse gases emitted in the production and trade. The use of these resources also includes a wide range of impacts not included in the analysis. For example, one of the major environmental impacts related to water use in agriculture are the impacts related to water quality (such as eutrophication and chemical pollution due to the use of pesticides and herbicides). However, they were not included in the analysis because of data availability constraints and the inappropriateness of the used methodology. Although water footprint methodology includes the aspect of the water quality in the concept of grey water, its calculation and estimation has a different logic compared to the analysis of green and blue water and it includes a wide range of uncertainties for example related to the maximum acceptable concentrations of pollutants (Liu et al., 2012). However, because the water quality impacts caused by agriculture are a key concern (see e.g. Bennett et al., 2001; Tilman et al., 2001), their inclusion also in the telecoupling studies should be high on the agenda for the future research.

An alternative to the physical material flow accounting applied is to use economic modelling and environmentally extended multi-region input-output analyses (MRIO) that are also widely used for consumption based accounting of resource use. MRIO methods are based on the financial transaction flows between economic sectors (Wiedmann et al., 2011). Economic modelling has been previously applied in studies about the greenhouse gases and material flows embodied in Finnish trade (Koskela et al., 2011; Mattila and Saikku, submitted; Mäenpää and Siikavirta, 2007; Seppälä et al., 2011).

Mattila and Saikku (submitted) analyzed the land use embedded in Finnish imports comparing two MRIO-based methods and a LCA method based on physical accounting. Our results for imported cropland from Paper I and II are in line with their results from the LCA method estimating that the cropland use embedded in Finnish crop imports in 2010 was almost 6 000 km^2. The MRIO-based results report numbers more than three times higher, more than 21 000 km^2 (Mattila and Saikku, submitted). The differences in the results are most likely related to the main differences between the two approaches: the units of measuring the flows and the scope of the analysis. First, MRIO accounts assess also the indirect resource use and the upstream material requirements, while physical accounting considers only the direct resource use within the sector. Second, the differences might be related to the dimension and composition used in the analysis. MRIO accounts assign the same land demand to each dollar of production in a sector. In contrast, the accounts based on physical trade data assign the same amount of land to one mass unit of a product, usually specified at the level of individual crops and not aggregated sectors (Kastner et al., 2014b). For example, MRIO method assigns different land demand for the same product with different prices, while physical accounting will only consider the amount of crops used assigning an equal amount of land per resource use.

The distinct metrics (such as embodied cropland, water, greenhouse gas emissions or dollars) used in an analysis produce distinct results and conclusions (MacDonald et al., 2015). This was also the case for example when analyzing the biodiversity threat hotspots related to cropland use or irrigation water use (Paper III). The choice of indicator or metrics analyzed in a study can alter results and conclusions drawn and it should be carefully assessed especially with high-value crop commodities and animal products, for which values differ considerably from biophysical metrics (MacDonald et al., 2015). Therefore, the benefits and limitations related to specific metrics should be given more consideration and the use of multiple metrics should be encouraged (MacDonald et al., 2015). The focus of the research in this dissertation has been on the environmental aspects of sustainability. However, the cultural, social and economic aspects of the telecouplings are as well important issues to consider and the findings of this dissertation should be combined with studies focusing on these and other missing aspects, to support a more comprehensive consumption and decision-making.

6. Conclusions

Food systems affect and are affected by the complex sustainability problems such as climate change, natural resource depletion, biodiversity loss and rapid urbanization. With the increasing human population and globalization that intensifies global trade, the complexity and scale of these challenges has increased. In food systems the most severe environmental impacts related to land or water use or the GHG emissions caused, often take place in the production areas. However, international trade complicates the tracing of products, and makes it difficult to link the impacts to sometimes geographically distant consumption. Yet, consumption is often the underlying driver also in the environmental change taking place in the production areas. Therefore, with the increasing globalization, the need for consumption-based accounting and its development, is evident.

This dissertation focuses on producing quantitative estimates and expanding the understanding of the interconnections and the global consequences of the Finnish food consumption. It was found that, Finland has become strongly connected to the global food markets both as an importer and as an exporter of agricultural commodities. Therefore, the sustainability of the Finnish food systems is increasingly depending on the sustainability of also the food systems abroad. Although the majority of the food imports into Finland comes from close-by countries, some of the highest impacts e.g. related to global biodiversity loss are caused further away in other continents. This highlights the need to further develop and improve the tools and approaches to estimate also the distant impacts, in a way that sustainable consumption would be made as easy as possible for consumers and decision-makers.

Dietary change provides a powerful consumer-side action to transform food systems to a more sustainable direction. When analyzing in more detail the composition of current diets in the EU, the results of previous studies were confirmed: animal products, especially beef and dairy consumption are related to the highest share of dietary greenhouse gas footprints. This is both because of direct emissions from production and also indirectly through feed production. Their consumption is also related to higher land and water use compared to average plant based products. Therefore, a reduction of animal product consumption provides a potential to reduce the environmental pressure caused by food consumption.

The findings of this thesis can be seen as one awakening step towards change. They highlight the need for broadening viewpoints, including different systemic levels and analyzing the local consumption also within global context and in connection with other systems. Different indicators emphasize different aspects of environmental pressure caused and reveal differences in the results. Therefore, systemic and other comprehensive analyses integrating multiple indicators and different spatial and temporal scales are increasingly needed to support sustainable food systems locally as well as globally.

Transition towards a more sustainable food production, consumption and trade to secure healthy and nutritionally balanced food supply for the growing population with less environmental cost is challenging, but urgently necessary task for human societies. Many kinds of strategies and solutions are needed, from technical improvements to consumption changes and even larger systemic changes. Globalization will most probably continue intensifying the telecouplings between distant areas. Instead of just facilitating the displacement of negative environmental impacts, its power could be harnessed to reduce environmental and other negative impacts by making good use of the benefits of different production regions, such as resource efficiency and natural resource availability, and to spread equity, good practices and innovations of sustainable development across countries. This should be done assuring a more fair and equitable distribution of the income to the whole supply chain and securing the long-term sustainability of the practices and systems in the production countries. However, as the human activities continue pushing the Earth's limits beyond safe operating space, major changes needs to take place very soon.

References

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M. D. (2017). Losses, inefficiencies and waste in the global food system. Agricultural systems, 153, 190-200.

Allen, P. M. (2001). The dynamics of knowledge and ignorance: learning the new systems science. In Integrative systems approaches to natural and social dynamics (pp. 3-29). Springer Berlin Heidelberg.

Allenby, B. (2006). The ontologies of industrial ecology? Progress in Industrial Ecology – An International Journal, 3 (1/2), 28–40.

Al-Rodhan, N. R., & Stoudmann, G. (2006). Definitions of globalization: A comprehensive overview and a proposed definition. Program on the Geopolitical Implications of Globalization and Transnational Security, 6, 1-21.

Anderson, K. (2010). Globalization's effects on world agricultural trade, 1960–2050. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 365(1554), 3007-3021.

Angstrom A (1935) Teleconnections of climatic changes in present time. Geogr Annal 17:243–258

Archer, M., Bhaskar, R., Collier, A., Lawson, T., & Norrie, A. (Eds.). (2013). Critical realism: Essential readings. Routledge.

Arima, E. Y., Richards, P., Walker, R., & Caldas, M. M. (2011). Statistical confirmation of indirect land use change in the Brazilian Amazon. Environmental Research Letters, 6(2), 024010.

Aston, L. M., Smith, J. N., & Powles, J. W. (2012). Impact of a reduced red and processed meat dietary pattern on disease risks and greenhouse gas emissions in the UK: a modelling study. BMJ open, 2(5), e001072.

Audsley, E., Brander, M., Chatterton, J. C., Murphy-Bokern, D., Webster, C., & Williams, A. G. (2010). How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050. Report for the WWF and Food Climate Research Network.

Bennett, E. M., Carpenter, S. R., & Caraco, N. F. (2001). Human impact on erodable phosphorus and eutrophication: a global perspective: increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. AIBS Bulletin, 51(3), 227-234.

Bhagwati, J. (2004). In defense of globalization: With a new afterword. Oxford University Press.

Bradford, G. E. (1999). Contributions of animal agriculture to meeting global human food demand. Livestock Production Science, 59(2), 95-112.

Bruckner, M., Fischer, G., Tramberend, S., & Giljum, S. (2015). Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. Ecological Economics, 114, 11-21

Bryngelsson, D., Wirsenius, S., Hedenus, F., & Sonesson, U. (2016). How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. Food Policy, 59, 152-164.

Cairns Jr, J. (2004). Sustainability and specialization. Ethics in Science and Environmental Politics, 1, 33-38.

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A, Havlik, P., O'Connel, C. S., Johnson, J. A., Saatchi, S. & West, P. C. (2017). Greenhouse gas emissions intensity of global croplands. Nature Climate Change, 7(1), 63.

Carlsson-Kanyama, A., Ekström, M. P., & Shanahan, H. (2003). Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecological economics, 44(2-3), 293-307.

Carlsson-Kanyama, A., & González, A. D. (2009). Potential contributions of food consumption patterns to climate change–. The American journal of clinical nutrition, 89(5), 1704S-1709S.

Chaudhary, A., Pfister, S., & Hellweg, S. (2016). Spatially explicit analysis of biodiversity loss due to global agriculture, pasture and forest land use from a producer and consumer perspective. Environmental science & technology, 50(7), 3928-3936.

Cristea, A., Hummels, D., Puzzello, L., & Avetisyan, M. (2013). Trade and the greenhouse gas emissions from international freight transport. Journal of Environmental Economics and Management, 65(1), 153-173.

COMTRADE, 2013. United Nations Commodity Trade Statistics Database. COMTRADE, http://comtrade.un.org. Accessed: 1.12.2013

Crutzen, P. J. (2002). Geology of mankind. Nature, 415(6867), 23.

Cumming, G. S., Cumming, D. H., & Redman, C. L. (2006). Scale mismatches in social-ecological systems: causes, consequences, and solutions. Ecology and society, 11(1).

Cuypers, D., Geerken, T., Gorissen, L., Lust, A., Peters, G., Karstensen, J., Prieler, S., Fisher, G., Hizsnyik, E., & Van Velthuizen, H. (2013). The impact of EU consumption on deforestation: Comprehensive analysis of the impact of EU consumption on deforestation.

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., & Rodriguez-Iturbe, I. (2012). Evolution of the global virtual water trade network. Proceedings of the National Academy of Sciences, 109(16), 5989-5994.

Das, D. K. (2004). Economic dimensions of globalization. In The Economic Dimensions of Globalization (pp. 67-102). Palgrave Macmillan, London.

Davis, K. F., Gephart, J. A., Emery, K. A., Leach, A. M., Galloway, J. N., & D'Odorico, P. (2016). Meeting future food demand with current agricultural resources. Global Environmental Change, 39, 125-132.

DeFries, R. S., Rudel, T., Uriarte, M., & Hansen, M. (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nature Geoscience, 3(3), 178.

DeFries, R., Herold, M., Verchot, L., Macedo, M. N., & Shimabukuro, Y. (2013). Export-oriented deforestation in Mato Grosso: harbinger or exception for other tropical forests?. Philosophical Transactions of the Royal Society B: Biological Sciences, 368(1619), 20120173.

de Visser, C. L. M., Schreuder, R., & Stoddard, F. (2014). The EU's dependency on soya bean import for the animal feed industry and potential for EU produced alternatives. OCL 21, D407. doi: https://doi.org/10.1051/ocl/2014021

D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L., & Vandoni, S. (2014). Feeding humanity through global food trade. Earth's Future, 2(9), 458-469.

Döll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environmental Research Letters 4, 035006.

Eakin, H., DeFries, R., Kerr, S., Lambin, E. F., Liu, J., Marcotullio, P. J., Messerli, P., Reenberg, A., Rueda, X., Swaffield, S. R., Wicke, B. & Zimmerer K. (2014). Significance of telecoupling for exploration of land-use change. In Rethinking global land use in an urban era. MIT Press.

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Hayama, Japan.

Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. Global environmental change, 18(1), 234-245.

Eshel, G., & Martin, P. A. (2006). Diet, energy, and global warming. Earth Interactions, 10(9), 1-17.

Falkenmark, M., Lundqvist, J.& Widstrand, C. (1989). Macro-scale water scarcity requires micro-scale approaches. Natural resources forum, 13(4), 258-267.

Flood, R. L. (2010). The relationship of 'systems thinking'to action research. Systemic Practice and Action Research, 23(4), 269-284.

FAO, Food and Agriculture Organization of the United Nations (FAO) (2001). Food balance sheets. A handbook. Food and Agriculture Organization of the United Nations, Rome. [Available at: http://www.fao.org/docrep/003/x9892e/X9892E00.htm]. Accessed: 1.6.2018.

FAO, IFAD, UNICEF, WFP and WHO. 2017. The State of Food Security and Nutrition in the World 2017.Building resilience for peace and food security. Rome, FAO. [Available at: http://www.fao.org/3/a-I7695e.pdf] Accessed: 1.6.2018.

FAO, Food and Agriculture Organization of the United Nations (FAO) (2018). Statistic Division. [Available at: www.faostat.org]. Accessed: 1.6.2018.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O´Connel, C., Ray, D. K., West, P. C., Balzer, C., Bennet, E. M., Carpenter, J. H., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. M. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. Annu. Rev. Environ. Resour., 30, 441-473.

Friis, C., Nielsen, J. Ø., Otero, I., Haberl, H., Niewöhner, J., & Hostert, P. (2016). From teleconnection to telecoupling: taking stock of an emerging framework in land system science. Journal of Land Use Science, 11(2), 131-153.

Friis, C., & Nielsen, J. Ø. (2017). On the System. Boundary Choices, Implications, and Solutions in Telecoupling Land Use Change Research. Sustainability, 9(6), 974.

Furman, E., Häyhä, T., & Hirvilammi, T. (2018). A future the planet can accommodate. Views on environmental policy. Syke policy brief. Finnish environment institute.

Gabel, V.M., Meier, M.S., Köpke, U., Stolze, M., 2016. The challenges of including impacts on biodiversity in agricultural life cycle assessments. J. Environ. Manag. 181 (1), 249–260.

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A., Havlik, P., O'Connel, C. S., Johnson, J. A., Saatchi, S., & West, P. C. (2017). Greenhouse gas emissions intensity of global croplands. Nature Climate Change, 7(1), 63.

Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., & Foley, J. A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences, 107(38), 16732-16737.

Godar, J., Persson, U. M., Tizado, E. J., & Meyfroidt, P. (2015). Towards more accurate and policy relevant footprint analyses: tracing fine-scale socio-environmental impacts of production to consumption. Ecological Economics, 112, 25-35.

Godar, J., Suavet, C., Gardner, T. A., Dawkins, E., & Meyfroidt, P. (2016). Balancing detail and scale in assessing transparency to improve the governance of agricultural commodity supply chains. Environmental Research Letters, 11(3), 035015.

Goleman, D. 2009. Ecological Intelligence – Knowing the hidden impacts of what we buy. Broadway books, the Crown Publishing Group, Random House, Inc. New York.

González, A. D., Frostell, B., & Carlsson-Kanyama, A. (2011). Protein efficiency per unit energy and per unit greenhouse gas emissions: potential contribution of diet choices to climate change mitigation. Food Policy, 36(5), 562-570.

Graedel, T. E., & Allenby, B. R. (1995). Industrial ecology. Englewood Cliffs: Prentice Hall.

Graedel, T. E., & Allenby, B. R. (2003) Industrial Ecology. Upper Saddle River, N.J: Prentice Hall cop. 2nd ed.

Guba, E.G. 1990. The Alternative Paradigm Dialog. Pp. 17-27 in Guba, E.G. (ed): The Paradigm Dialog. Sage Publications, Newbury Park, London, New Delhi.

Gunarso, P., Hartoyo, M. E., Agus, F., & Killeen, T. (2013). Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea. Reports from the Technical Panels of the 2nd greenhouse gas working Group of the Roundtable on Sustainable Palm Oil (RSPO) (pp. 29–64). Singapore.

Haapanen, L., & Tapio, P. (2016). Economic growth as phenomenon, institution and ideology: a qualitative content analysis of the 21st century growth critique. Journal of Cleaner Production, 112, 3492-3503.

Haines, A., McMichael, A. J., Smith, K. R., Roberts, I., Woodcock, J., Markandya, A., Armstrong, B. G.,Campbell-Lendrum, D., Dangour, A., Davies, M., Bruce, N., Tonne, C., Barret, M. & Wilkinson, P. (2010). Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. The Lancet, 374(9707), 2104-2114.

Hallström, E., Carlsson-Kanyama, A., & Börjesson, P. (2015). Environmental impact of dietary change: a systematic review. Journal of Cleaner Production, 91, 1-11.

Heerwagen, J.H. & Orians, G. H. (1993) Humans, habitats and aesthetics. In: Kellert SR, Wilson EO (eds) The biophilia hypothesis. Island Press, Washington, DC, p 138–172.

Heffer P. (2013) Assessment of fertilizer use by crop at the global level 2010-2010/11. http://www.fertilizer.org/En/Statistics/FUBC.aspx. Accessed on July 10, 2016.

Heller, M. C., & Keoleian, G. A. (2015). Greenhouse gas emission estimates of US dietary choices and food loss. Journal of Industrial Ecology, 19(3), 391-401.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., Blummel, M., Weiss, F., Grace, D.,& Obersteiner, M. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences, 110(52), 20888-20893.

Hertwich, E. G., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade-linked analysis. Environmental science & technology, 43(16), 6414-6420.

Hoekstra, A.Y. (2003). Virtual water: An introduction. In Virtual water trade: Proceedings of the international expert meeting on virtual water trade. Value of water research report series (11), 13-23.

Hoekstra, A. Y. (2016). A critique on the water-scarcity weighted water footprint in LCA. Ecological indicators, 66, 564-573.

Hoff, H., Nykvist, B., & Carson, M. (2014). "Living well, within the limits of our planet"? Measuring Europe's growing external footprint. Stockholm Environment Institute, 2014-5.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. Environmental Research Letters, 7(4), 044009.

Hyrylä, L. (2016). Elintarviketeollisuus. Toimialaraportti 7/2016. Työ-ja elinkeinoministeriö. [Available at: http://urn.fi/URN:ISBN:978-952-327-159-3] Accessed: 1.8.2018.

Ison, R. (2008). Systems thinking and practice for action research. In The Sage Handbook of Action Research Participative Inquiry and Practice, 2nd ed.; Reason, P.W., Bradbury, H., Eds.; Sage Publications: London, UK, pp. 139–158.

Jalava, M., Kummu, M., Porkka, M., Siebert, S., & Varis, O. (2014). Diet change—a solution to reduce water use?. Environmental research letters, 9(7), 074016.

Karlsson, J., Röös, E., Sjunnestrand, T., Pira, K., Larsson, M., Andersen, B. H., Sorensen, J., Veistola, T., Rantakokko, J., Manninen, S. & Brubæk, S. (2017). Future Nordic Diets: Exploring ways for sustainably feeding the Nordics (Vol. 2017566). Nordic Council of Ministers. Copenhagen, Denmark.

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Grubler, A., Huntley, B., Jäger, J., Jodha, N. S., Kasperson, R. E., Mabogunje, A., Matson, P., Mooney, H., Moore III, B., O'Riordan, T. & Svedin, U. (2001). Sustainability science. Science, 292(5517), 641-642.

Kastner, T., Kastner, M., & Nonhebel, S. (2011). Tracing distant environmental impacts of agricultural products from a consumer perspective. Ecological Economics, 70(6), 1032-1040.

Kastner, T., Erb, K. H., & Haberl, H. (2014a). Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environmental Research Letters, 9(3), 034015

Kastner, T., Schaffartzik, A., Eisenmenger, N., Erb, K. H., Haberl, H., & Krausmann, F. (2014b). Cropland area embodied in international trade: Contradictory results from different approaches. Ecological Economics, 104, 140-144.

Kauffman, J. (2009). Advancing sustainability science: report on the International Conference on Sustainability Science (ICSS) 2009. Sustainability Science, 4(2), 233.

Kier, G., Kreft, H., Lee, T.M., Jetz,W., Ibisch, P.L., Nowicki, C.,Mutke, J., Barthlott,W. (2009). A global assessment of endemism and species richness across island and mainland regions. Proc. Natl. Sci. Unit. States. Am. 106 (23), 9322–9327.

Kissinger, M., & Rees, W. E. (2010). An interregional ecological approach for modelling sustainability in a globalizing world—Reviewing existing approaches and emerging directions. Ecological Modelling, 221(21), 2615-2623.

Koskela, S., Mäenpää, I., Seppälä, J., Mattila, T., & Korhonen, M. R. (2011). EE-IO modeling of the environmental impacts of Finnish imports using different data sources. Ecological Economics, 70(12), 2341-2349.

Kummu, M., Ward, P.J., de Moel, H., & Varis, O. (2010). Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. Environmental Research Letters 5, 034006.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., & Ward, P. J. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Science of the total environment, 438, 477-489.

Kummu, M., Gerten, D., Heinke, J., Konzmann, M., & Varis, O. (2014). Climate-driven interannual variability of water scarcity in food production potential: a global analysis. Hydrology and Earth System Sciences 18, 447-461.

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences, 108(9), 3465-3472.

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., & Geschke, A. (2012). International trade drives biodiversity threats in developing nations. Nature, 486(7401), 109-112.

Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., & Foran, B. (2013). International trade of scarce water. Ecological Economics, 94, 78-85.

Liu, C., Kroeze, C., Hoekstra, A. Y., & Gerbens-Leenes, W. (2012). Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. Ecological indicators, 18, 42-49.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H. & Taylor, W. W. (2007). Complexity of coupled human and natural systems. science, 317(5844), 1513-1516.

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, R., Izaurralde, C., Lambin, E. F., Li, S., Martinelli, L. A., McConnell, W. J., Moran, E. F., Naylor, R., Ouyang, Z., Polenske, K. R., Reenberg, A., de Miranda Rocha, G., Simmons, C. S., Verburg, P. H., Vitousek, F. Z., Zhang, F.. & Zhu, C. (2013). Framing sustainability in a telecoupled world. Ecology and Society, 18(2).

Liu, J., Hull, V., Luo, J., Yang, W., Liu, W., Viña, A., Vogt, C., Xu, Z., Yang, H., Zhang, J., An, L., Chen, X., Li, S., Oyang, Z., Xu, W., & Zhang, H. (2015). Multiple telecouplings and their complex interrelationships. Ecology and Society, 20(3).

MacDonald, G. K., Brauman, K. A., Sun, S., Carlson, K. M., Cassidy, E. S., Gerber, J. S., & West, P. C. (2015). Rethinking agricultural trade relationships in an era of globalization. BioScience, 65(3), 275-289

Mattila, T. & Saikku, L. How much land does Finland import? Estimating upstream land use with different MRIO and LCA data sources. submitted manusript.

Mayer, A. L., Kauppi, P. E., Angelstam, P. K., Zhang, Y., & Tikka, P. M. (2005). Importing timber, exporting ecological impact.

Mayer, A. L., Kauppi, P. E., Tikka, P. M., & Angelstam, P. K. (2006). Conservation implications of exporting domestic wood harvest to neighboring countries. Environmental science & policy, 9(3), 228-236.

Mekonnen, M.M. & Hoekstra, A.Y. (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrology and Earth System Sciences, 15(5): 1577-1600.

Mekonnen, M.M., Hoekstra, A.Y. (2016) Four billion people facing severe water scarcity. Science Advances 2: e1500323.

Meyfroidt, P., & Lambin, E. F. (2009). Forest transition in Vietnam and displacement of deforestation abroad. Proceedings of the National Academy of Sciences, 106(38), 16139-16144.

Meyfroidt, P., Rudel, T., Lambin, E. (2010). Forest transitions, trade, and the global displacement of land use. Proceedings of the National Academy of Sciences of the United States of America 107, 20917–20922.

Meyfroidt, P., Lambin, E. F., Erb, K. H., & Hertel, T. W. (2013). Globalization of land use: distant drivers of land change and geographic displacement of land use. Current Opinion in Environmental Sustainability, 5(5), 438-444.

MMM, Ministry of Agriculture and Forestry of Finland. (2016). Kansallinen viljastrategia 2012–2020. Helsinki. [National Cereal Strategy 2012-2010, In Finnish]. Available online: https://www.vyr.fi/document/1/124/dc2fa51/viljas_dfa7a15_32637_KansallinenViljastrategia_net.pdf.

Moser, S. C., & Hart, J. A. F. (2015). The long arm of climate change: societal teleconnections and the future of climate change impacts studies. *Climatic Change*, *129*(1-2), 13-26.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., & Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security, 14, 1-8

Myers, R. A., & Worm, B. (2003). Rapid worldwide depletion of predatory fish communities. Nature, 423(6937), 280.

Mäenpää, I., & Siikavirta, H. (2007). Greenhouse gases embodied in the international trade and final consumption of Finland: an input–output analysis. Energy Policy, 35(1), 128-143.

Naylor, R. L., Goldburg, R. J., Primavera, J. H., Kautsky, N., Beveridge, M. C., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. (2000). Effect of aquaculture on world fish supplies. Nature, 405(6790), 1017.

Niemi, J., Knuuttila, M., Liesivaara, P. & Vatanen, E. (2013). Finland's food security and maintenance and supply security: the current situation and future prospects. MTT Agrifood Research Finland, Jokioinen, Finland.

Nikula, J. (2012). Suomen vesijalanjälki: Globaali kuva suomalaisten vedenkulutuksesta. Helsinki: WWF Suomi.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. Nature Sustainability, 1(2), 88.

OSF, Official Statistics of Finland, 2017. Balance Sheet for Food Commodities. Natural Resources Institute Finland, Helsinki. [Available at: http://stat.luke.fi/en/balance%20sheet%20for%20food%20commodities] Accessed: 1.6.2018.

OSF, Official Statistics of Finland, 2018a. Utilised Agricultural Area [e-publication]. Natural Resources Institute Finland, Helsinki. [Available at: http://stat.luke.fi/en/utilised-agricultural-area Accessed: 1.6.2018.

OSF, Official Statistics of Finland, 2018b. [Available at: https://www.tilastokeskus.fi/meta/svt/index_en.html Accessed: 1.6.2018.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science, 325(5939), 419-422.

Peltonen-Sainio, P., Jauhiainen, L., Hannukkala, A. (2007). Declining rapeseed yields in Finland: how, why and what next? J. Agric. Sci. 145, 587–598.

Peltonen-Sainio, P., Hannukkala, A., Huusela-Veistola, E., Voutila, L., Niemi, J., Valaja, J. et al. (2013). Potential and realities of enhancing rapeseed-and grain legume-based protein production in a northern climate. The Journal of Agricultural Science 151, 303–321.

Peltonen-Sainio, P., Jauhiainen, L., & Lehtonen, H. (2016). Land Use, Yield and Quality Changes of Minor Field Crops: Is There Superseded Potential to Be Reinvented in Northern Europe? PloS one 11, e0166403.

Peltonen-Sainio, P., Jauhiainen, L., & Sorvali, J. (2017). Diversity of high-latitude agricultural landscapes and crop rotations: Increased, decreased or back and forth? Agricultural Systems 154, 25-33.

Perignon, M., Masset, G., Ferrari, G., Barré, T., Vieux, F., Maillot, M., Amiot, M-J. & Darmon, N. (2016). How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices. Public Health Nutrition, 19(4), 1-13.

Peters, G. P., & Hertwich, E. G. (2008). CO_2 embodied in international trade with implications for global climate policy.

Pfister, S., Koehler, A., Hellweg, S., (2009). Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43 (11), 4098–4104.

Persson, U. M., Henders, S., & Cederberg, C. (2014). A method for calculating a land-use change carbon footprint (LUC-CFP) for agricultural commodities–applications to Brazilian beef and soy, Indonesian palm oil. Global change biology, 20(11), 3482-3491.

Porkka, M., Kummu, M., Siebert, S., & Varis, O. (2013). From food insufficiency towards trade dependency: a historical analysis of global food availability. PloS one, 8(12), e82714.

Porkka, M., Guillaume, J. H., Siebert, S., Schaphoff, S., & Kummu, M. (2017). The use of food imports to overcome local limits to growth. Earth's Future, 5(4), 393-407.

Pradhan, P., Reusser, D. E., & Kropp, J. P. (2013). Embodied greenhouse gas emissions in diets. PloS one, 8(5), e62228.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A. (2008). Farming the planet:geographic distribution of global agricultural lands in the year 2000. GlobalBiogeochemical Cycles 22, GB1003, doi: http://dx.doi.org/10.1029/2007GB002952.

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H. (2018). Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. Annual review of plant biology, 69, 789-815.

Reid, W.V. et al. (2005). Millennium Ecosystem Assessment: Ecosystems and Human Well-Being—Synthesis Report. World Resources Institute, Washington, DC, 2005.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).

Seekell, D., Carr, J., Dell'Angelo, J., D'Odorico, P., Fader, M., Gephart, J., Kummu M., Magliocca, N., Porkka, M. & Puma, M. (2017). Resilience in the global food system. Environmental Research Letters, 12(2), 025010.

Seppälä, J., Mäenpää, I., Koskela, S., Mattila, T., Nissinen, A., Katajajuuri, J. M., Härmä, T., Korhonen, M.-R., Saarinen, M. & Virtanen, Y. (2011). An assessment of greenhouse gas emissions and material flows caused by the Finnish economy using the ENVIMAT model. Journal of Cleaner Production, 19(16), 1833-1841.

Seto, K. C., Reenberg, A., Boone, C. G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D. K., Olah, B. & Simon, D. (2012). Urban land teleconnections and sustainability. Proceedings of the National Academy of Sciences, 109(20), 7687-7692.

Spangenberg, J. H. (2011). Sustainability science: a review, an analysis and some empirical lessons. Environmental Conservation, 38(3), 275-287.

Steffen, W., Crutzen, P. J., & McNeill, J. R. (2007). The Anthropocene: are humans now overwhelming the great forces of nature. AMBIO: A Journal of the Human Environment, 36(8), 614-621.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B. & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223), 1259855.

Stehfest, E., Bouwman, L., Van Vuuren, D. P., Den Elzen, M. G., Eickhout, B., & Kabat, P. (2009). Climate benefits of changing diet. Climatic Change, 95(1), 83-102.

Tilman, D., Fargione, J., Wolff, B., D'antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D. & Swackhamer, D. (2001). Forecasting agriculturally driven global environmental change. Science, 292(5515), 281-284.

Tom, M. S., Fischbeck, P. S., & Hendrickson, C. T. (2016). Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. Environment Systems and Decisions, 36(1), 92-103.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A. & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. Proceedings of the national academy of sciences, 100(14), 8074-8079.

United Nations Framework Convention on Climate Change (UNFCCC). (2016), http://unfccc.int/ghg_data/items/3800.php. Accessed on July 10, 2016.

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N. & Hamlinck, C. (2015). The land use change impact of biofuels consumed in the EU: Quantification of area and greenhouse gas impacts.

Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. (2012). Climate change and food systems. Annual Review of Environment and Resources, 37.

Verones, F., Saner, D., Pfister, S., Baisero, D., Rondinini, C., Hellweg, S., 2013. Effects of consumptive water use on biodiversity in wetlands of international importance. Environ. Sci. Technol. 47 (21), 12248–12257.

Verones, F., Moran, D., Stadler, K., Kanemoto, K., & Wood, R. (2017a). Resource footprints and their ecosystem consequences. Scientific reports, 7, 40743.

Verones, F., Pfister, S., van Zelm, R., & Hellweg, S. (2017b). Biodiversity impacts from water consumption on a global scale for use in life cycle assessment. The International Journal of Life Cycle Assessment, 22(8), 1247-1256.

Weinzettel, J., Hertwich, E. G., Peters, G. P., Steen-Olsen, K., & Galli, A. (2013). Affluence drives the global displacement of land use. Global Environmental Change, 23(2), 433-438.

White, R. (1994). Preface. In B. Allenby & D. Richards (Eds.), The greening of industrial ecosystems. Washington, DC: National Academy Press.

Winter, L., Lehmann, A., Finogenova, N., & Finkbeiner, M. (2017). Including biodiversity in life cycle assessment–State of the art, gaps and research needs. Environmental Impact Assessment Review, 67, 88-100.

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. Ecological Economics, 70(11), 1937-1945.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. Proceedings of the National Academy of Sciences, 112(20), 6271-6276.

Willamo, R., Helenius, L., Holmström, C., Haapanen, L., Sandström, V., Huotari, E., Kaarre, K., Värre, U., Happonen, J. & Kolehmainen, L. (2018). Learning how to understand complexity and deal with sustainability challenges–A framework for a comprehensive approach and its application in university education. Ecological Modelling, 370, 1-13.

Willamo, R., 2005. Kokonaisvaltainen lähestymistapa ympäristönsuojelutieteessä (in Finnish, English abstract). Environmentalica Fennica 23. Doctoral Dissertation. University of Helsinki.

Wirsenius, S., 2000. Human use of land and organic materials: modeling the turnoverof biomass in the global food system. In: Ph.D. Dissertation. Chalmers Universityof Technology, Göteborg, Sweden.

Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., & Tukker, A. (2018). Growth in environmental footprints and environmental impacts embodied in trade: Resource efficiency indicators from EXIOBASE3. Journal of Industrial Ecology.

World Bank, (2018), World Bank Open Data. [Available at: https://data.worldbank.org/] Accessed: 1.6.2018

World Health Organization (WHO) (2018). Global Health Observatory data [Available at: World Hehttp://www.who.int/gho/en/] Accessed: 1.6.2018.

Young, O., Lambin, E., Alcock, F., Haberl, H., Karlsson, S., McConnell, W., Myint, T., Pahl-Wostl, C., Polsky, C., Ramakrishnan, P. S., Schroeder, H., Scouvart, M. & Verburg, P H. (2006a). A portfolio approach to analyzing complex human-environment interactions: institutions and land change. Ecology and society, 11(2).

Young, O. R., Berkhout, F., Gallopin, G. C., Janssen, M. A., Ostrom, E., & Van der Leeuw, S. (2006b). The globalization of socio-ecological systems: an agenda for scientific research. Global Environmental Change, 16(3), 304-316.

Zhang, Z., Zhu, K., & Hewings, G. J. (2017). The effects of border-crossing frequencies associated with carbon footprints on border carbon adjustments. Energy Economics, 65, 105-114.